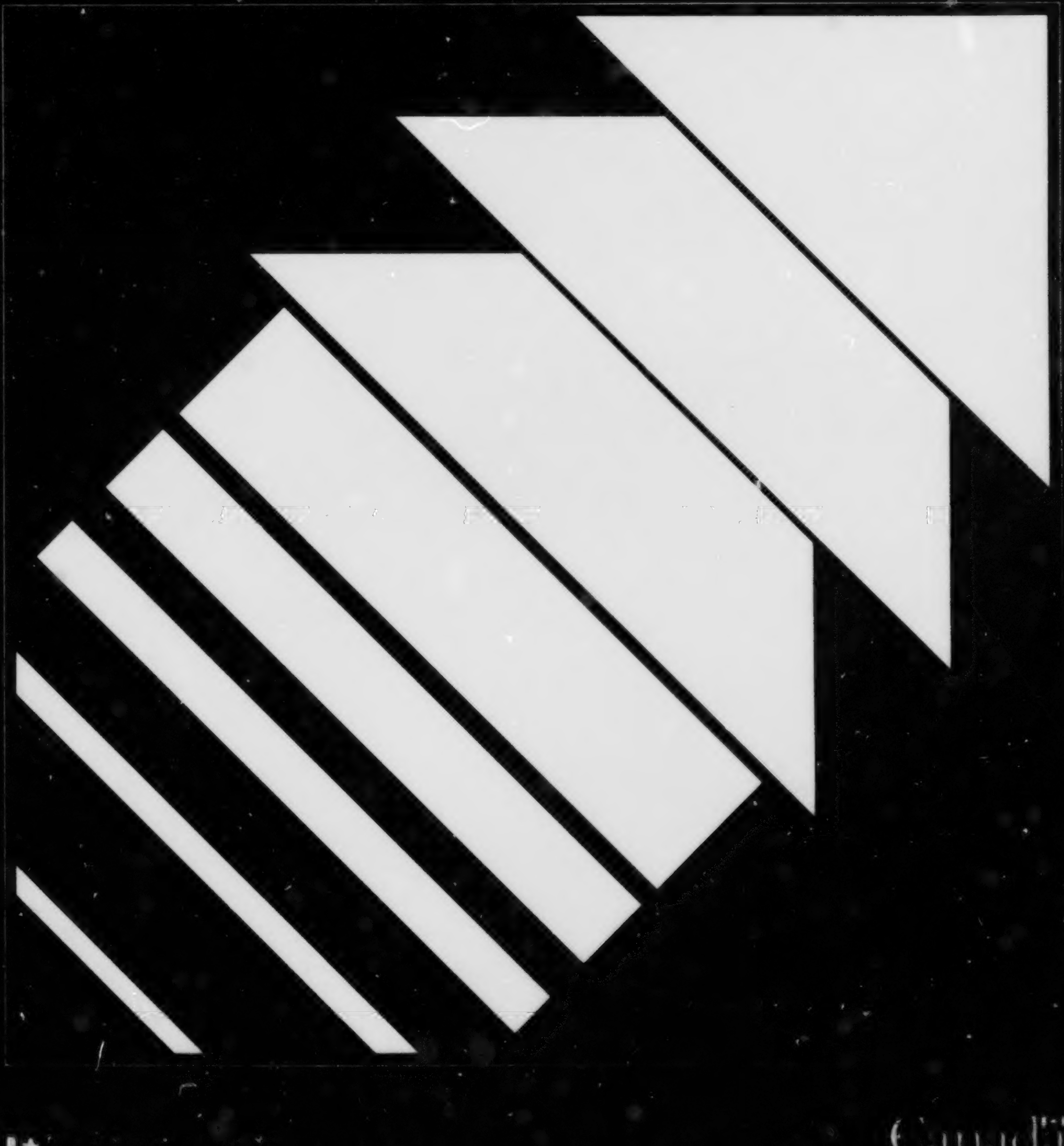
NATIONAL
URANIUM
TAILINGS
PROGRAM



Canadä

APPROACHES TO RISK ASSESSMENT FOR CANADIAN URANIUM MILL TAILINGS

DSS File #14SQ.23241-4-1695
Contract No. 0SQ84-00335

A Research Report prepared for:

The National Uranium Tailings Program
Canada Centre for Mineral and Energy Technology
Energy, Mines and Resources Canada
555 Booth Street
Ottawa, Ontario
K1A 0G1

by

SENES Consultants Limited
499 McNicoll Avenue
Willowdale, Ontario
M2H 2C9

October 1985

194 pp

MICROMEDIA

ABSTRACT

This report examines alternative ways of defining and comparing risks to individuals and populations arising from uranium mill tailings. The concept of risk as a set of triplets consisting of potential scenarios, the likelihood that each occurs and the consequence of each is introduced. Based on the triplet concept, a method of combining risks from different scenarios is presented and illustrated by application to a reference tailings site.

NOTICE

This report was prepared by SENES Consultants Limited (SENES) under contract to the National Uranium Tailings Program (NUTP). Neither the NUTP nor SENES makes any warranty, expressed or implied, or assumes any liability with respect to any damage or loss incurred as a result of the use made of the information contained in this publication.

ACKNOWLEDGEMENTS

Many people contributed to this study. The study was carried out under the direction of Mr. R.A. Knapp of SENES, who was project manager. Principal technical contributors from SENES included Dr. D.B. Chambers, M.L. Murray and Dr. L.M. Lowe.

Drs. R.V. Osborne and P.J. Barry prepared a discussion paper on risk concepts. Their assistance is gratefully acknowledged.

Dr. S. Kaplan developed the approach to combining risks and was the source of much useful insight into the risk assessment process. Dr. Kaplan's personal interest and effort in this study was very much appreciated.

Dr. M.G. Morgan, was kind enough to take time from his hectic schedule to provide a much needed broader perspective on risk analysis and risk management.

Finally we wish to thank Mr. W.C. Harrison and Mr. R.W. Holmes of the NUTP for their patience and many useful technical suggestions throughout the course of the study.

TABLE OF CONTENTS

Page No.

ABSTRACT i
NOTICE i
ACKNOWLEDGEMENTS ii
EXECUTIVE SUMMARY 1

1.0 INTRODUCTION 1-1
  1.1 Background 1-1
  1.2 Study Approach 1-2

2.0 SOME GENERAL CONSIDERATIONS OF RISK QUANTIFICATION AND ASSESSMENT 2-1
  2.1 What is Risk? 2-1
  2.2 Criteria for Limiting Risk 2-3
    2.2.1 Individual Limits 2-3
    2.2.2 Population Limits 2-6
  2.3 Some Issues in Optimization 2-7
    2.3.1 Discounting Future Dose 2-7
    2.3.2 Very Low Individual Dose 2-8
    2.3.3 Geographical Distribution of Dose 2-9
    2.3.4 Low Probability Events 2-9
    2.3.5 The Multicriteria Approach to Optimization 2-10

3.0 A CONCEPTUAL APPROACH TO COMBINING RISK 3-1
  3.1 Quantitative Definition of Risk 3-2
  3.2 Defining Scenarios 3-2
  3.3 Expressing Likelihood 3-4
  3.4 Expressing Consequences 3-5

Table of Contents (continued)

Page No.

4.0 APPLICATION TO CANADIAN URANIUM MILL TAILINGS 4-1
  4.1 Description of the Reference Facility 4-1
  4.2 Events Considered 4-2
  4.3 Receptors Considered 4-4
  4.4 Results 4-5
    4.4.1 Consequences of the Events 4-5
    4.4.2 Construction of Risk Curves 4-8

5.0 PRINCIPAL OBSERVATIONS AND RECOMMENDATIONS 5-1
  5.1 Principal Observations 5-1
  5.2 Recommendations 5-2

6.0 REFERENCES 6-1

APPENDIX A: Approaches to Risk Assessment for Uranium Mill Tailings. Prepared by R. V. Osborne and P. J. Barry, Chalk River Nuclear Laboratory.

APPENDIX B: Risk Assessment of Canadian Uranium Mill Tailings. Prepared by S. Kaplan, Kaplan Associates Inc. and D. B. Chambers, R. A. Knapp and L. M. Lowe, SENES Consultants Limited.

APPENDIX C: Description of Environmental Models Used to Illustrate an Approach to Risk Quantification and Assessment. Prepared by M. L. Murray, D. B. Chambers, and R. A. Knapp, SENES Consultants Limited.

APPENDIX D: Some Fundamental Issues in the Development of a Coherent Risk Management Strategy for Uranium Mill Tailings. Prepared by M.G. Morgan, Carnegie-Mellon University.

LIST OF FIGURES

		Follows Page
2.1	Criteria for Limiting Individual Risk	2-4
4.1	Schematic Illustration of Watershed Setting for the Reference Tailings Site	4-1
4.2	Time Varying Behaviour: Maximum Annual Dose to Reference Receptor	4-6
4.3	Maximum Annual Dose to Reference Receptor	4-6
4.4	Risk Event Tree (excluding intrusion)	4-8
4.5	Risk Consequence Curve: Maximum Annual Dose to Reference Receptor	4-12
4.6	Risk Consequence Curve: Cumulative (1000 yr) Population Dose (including intruder)	4-12

LIST OF TABLES

Follows Page

4.1 Probability of Natural Events 4-2

4.2 Summary of Results 4-6

EXECUTIVE SUMMARY

This report examines approaches to risk assessment for Canadian uranium mill tailings. Risks to humans and the environment from uranium mill tailings can arise in many different ways and be caused by many different events. Mathematical modelling and probabilistic analysis provides a framework for quantifying the effects, and associated uncertainties resulting from individual events. This study explored methods for combining the consequences associated with various events, to produce an overall estimate of the risk associated with a generic tailings site.

Since the field of risk analysis is relatively new and evolving rapidly, the report first presents an overview of relevant concepts as they relate to uranium mill tailings. Alternative methods for limiting the risk from tailings to both individuals and populations are explored. Limiting the risk to individuals requires that the risk to the most highly exposed individual (i.e. critical receptor) be sufficiently small. When comparing the risks to populations of different tailings management strategies, optimization procedures such as ALARA, or a generalized multi-attribute analysis may be applied.

The concept of risk as a set of triplets, consisting of scenarios (combinations of individual events), their likelihood of occurrence and their associated consequences is presented. This concept provides a methodology for combining the consequences of many events in a quantitative manner. Its usefulness is illustrated by application to a generic Canadian uranium tailings facility. In order to summarize the large volume of information generated during the analysis, several methods of presenting the results are proposed.

The study also identified a number of areas for continued investigation. The issue of incorporating time dependency into a risk analysis should be explored further. Attention should also be given to the interpretation and presentation of results, and their use by decision makers.

1.0 INTRODUCTION

1.1 Background

In 1982 Energy, Mines and Resources Canada established the National Uranium Tailings Program (NUTP) which is intended to pull together previous work on Canadian uranium mill tailings, to fund additional work where significant information gaps are found and to develop the capability to predict the long-term effects of tailings. Such evaluations require the use of mathematical models to simulate the behaviour of the real system(s).

Environmental models, however, are only partial representations of real systems and contain a number of parameters which are either only imperfectly known or are inherently variable by nature. Consequently, the results of all such calculations are uncertain. Uncertainties also arise when these models are used to predict effects over conditions and periods of time different from those for which the models and model parameters were developed. Also, uncertainty arises in modelling future events due to our inability to predict the future sequence and magnitude of rare events. Probabilistic analysis allows us to quantify some of the uncertainty associated with the long-term effects of uranium mill tailings and to generate frequency distributions of expected consequences (e.g. maximum annual dose to a specified receptor). Typically, such an analysis involves the simulation of one model site, or event, at a time.

The NUTP, in their request for proposal, indicated that work was required in several areas to help make the predictions from such models more useful in decision making. More specifically, they requested that the contractor explore specific ways of defining and comparing risks from uranium mill tailings and investigate how the risks arising from different scenarios could be combined to produce an overall picture for a specific site. Finally, the contractor was to illustrate the latter methodology by a worked example. These subjects form the basis of this report.

1.2 Study Approach

The early stages of this study involved the preparation of two discussion papers. The first paper, prepared by Drs. Osborne and Barry, addresses a number of conceptual issues related to the evaluation of risks associated with uranium mill tailings. These authors note that all human endeavours entail some risk and argue that the usefulness of an endeavour should outweigh its detrimental effects. Osborne and Barry discuss risk- based criteria for individuals as well as the ALARA principle and a multi-criteria approach to optimization.

The second discussion paper, prepared by Dr. S. Kaplan et al, outlines how risks from different scenarios can be combined and analysed. The paper describes a methodology that can be used to assess risk from uranium mill tailings. The concept is that risk can be defined quantitatively as a set of triplets which express the possible risk scenarios, the likelihoods of the scenarios, and the consequences of the scenarios. The way in which risks from different scenarios can be combined is also discussed. Finally, the approach is illustrated by application to a reference uranium mill tailings site.

To demonstrate the approaches to risk analysis, a simplified, though relatively realistic example was selected. Appendix C, prepared by Murray et al, describes the characteristics of the reference tailings site modelled, and the mathematical models used to simulate the effects of various natural events. Several different receptors were modelled and various consequences to these receptors were calculated.

The key observations from these papers, augmented, where appropriate, by reference to risk literature formed the basis for this report.

A cautionary note is required. The worked example presented in Appendix B, which is based on calculations summarized in Appendix C, is just that - an example - no more and no less. It was provided to illustrate the methodology and should not be construed as an actual risk assessment of a particular uranium mill tailings site.

2.0 SOME GENERAL CONSIDERATIONS OF RISK QUANTIFICATION AND ASSESSMENT

This chapter discusses several notions of risk and introduces the concepts of risk analysis and risk management. Some suggestions for risk criteria are provided, as are brief discussions related to assessing risk in the face of uncertainty, introducing events of low probability and optimization.

2.1 What is Risk?

Risk is a word that has many different meanings. Beninson and Lindell (1981) note that, "The English word "risk" has the double meaning of the nature of a harmful event and the probability of the event."

The term risk has been associated with the possibility of many kinds of harm, including among others financial loss, environmental damage, impaired health and loss of life. In this study, risk refers to the potential effects associated with uranium mill tailings. Although it is self evident, we often forget that all human activities entail some risk. Kaplan and Garrick (1981) point out, "...that we may make risk as small as we like by increasing the safeguards but may never, as a matter of principle, bring it to zero. Risk is never zero, but it can be small."

The concept of uncertainty is also integral to the meaning of the word "risk". Uncertainty arises in many ways, including: uncertainty associated with the choice of mathematical models used to simulate tailings behaviour, uncertainty in model parameter values and uncertainty from the intrinsically stochastic behaviour of nature. For example, we are uncertain about the amount of rain that will fall next year or whether or not a forest fire will occur at a particular location at some point in the future (and if it does, exactly when will it occur?). Risk analysis thus examines uncertain events with uncertain outcomes. The methods of probabilistic analysis, which provide an indication of the uncertainty in the outcome (i.e. the answers), are appropriate for this kind of problem. Crouch and Wilson (1982) visualize risk in the form of the equation:

$$\text{Risk} = \text{Probability} * \text{Severity} \qquad (2\text{-}1)$$

Osborne and Barry (Appendix A of this report) consider risk to an individual exposed to ionizing radiation as:

$$R = r.P.H \qquad (2\text{-}2)$$

where H is the dose received, P is the probability of receiving that dose, and r is a coefficient which relates dose to deleterious effects on health. In other words, risk (R) is the probability of a health effect. Indeed, for a distribution of doses, risk could be considered as the statistical expectation of a health effect.

Kaplan et al (see Appendix B of this report) consider that the concept of risk boils down to the following three questions:

1) What can happen? (s_i)
2) How likely is that to happen? (l_i)
3) If it does happen, what are the consequences? (x_i)

The answers to these questions may be written conveniently in the form of a triplet:

$$\langle s_i, l_i, x_i \rangle$$

Using brace brackets, $\{ \}$, to denote "set of", the risk (R) can then be expressed as the set of all such possible triplets, that is:

$$R = \{ \langle s_i, l_i, x_i \rangle \}$$

Morgan (1981) identifies a number of questions related to risk assessment and risk management.

1) How can the magnitude of the risks people face be known?
2) What techniques can be used to regulate or otherwise limit the levels of these risks?
3) To the extent that these risks can be controlled, what level of risk should be chosen?

4) Who should be responsible for managing the risks and what institutional arrangements should be used?

Morgan (1981) also notes that the nomenclature is not yet standard. He suggests that the first of these problems be called risk assessment, the second risk abatement, and the third and fourth risk management. Alternatively one might think of question 1 as risk evaluation, 2 and 3 as assessment and 4 as management. No matter how they are viewed, they certainly are highly interrelated.

2.2 Criteria for Limiting Risk

Osborne and Barry (see Appendix A) suggest that there are two constraints which must be recognized when considering dose limits designed to protect human health. First, individuals must be protected to an accepted level of safety. Secondly, expenditures and efforts to improve safety for all people can reasonably be expected to be similar to those throughout Canadian society. This latter is particularly appropriate when public funds are involved, directly or indirectly, in paying for safety. Put another way, the decision criterion (of acceptability) is to ensure that total social benefits are greater than or equal to total social costs.

2.2.1 Individual Limits

The probability that there will be any effect on health as a result of the existence of uranium mill tailings will depend on the magnitude of the radiation exposure that a person might receive. The magnitude of the exposure will depend partly on how far away from the tailings the exposure occurs and other assumptions concerning the tailings themselves, the local environment and the characteristics of the exposed group(s) of which an exposed person(s) is a member.

Osborne and Barry suggest that a pragmatic approach is to use the concept of a representative individual selected from a hypothetical critical group. The critical group is assumed to be located in a manner consistent with the initial institutional controls. That is, they reside as close to the facility as is reasonable or permitted by regulation. The probability of their exposure is taken as unity; hence they are sure of receiving some dose. The magnitude of the dose is not known with any certainty, but can be estimated using appropriate mathematical models. It is necessary to ensure that the probability of health effects in members of the critical group is below some limit, by considering all the possible combinations of all events leading to a health effect.

A probabilistic analysis produces a distribution of dose (for any particular scenario). We argue that one can properly consider this output as a (subjective) probability distribution. The risk represented by a probability distribution of dose, p(H), can be quantified as:

$$R = r \int_0^\infty H\, p(H) dH \qquad (2-3)$$

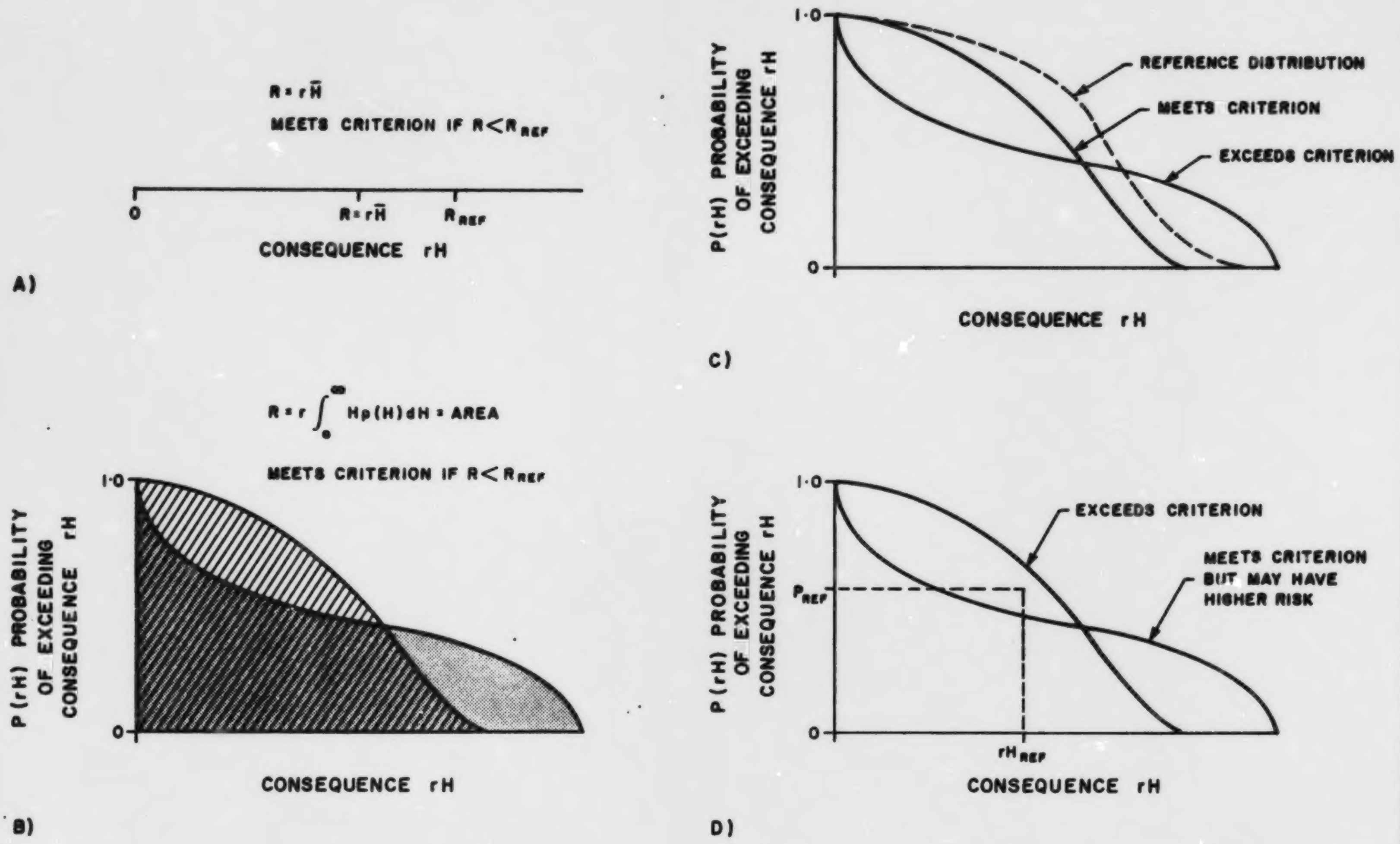
where R and r are as previously defined and r is taken as a constant. This is a reasonable simplification for radiation exposure in which a proportionality between probability of a health effect and radiation dose is assumed. The probability distribution p(H)dH may vary with time because of variations in some of the parameters in pathways models, or because of variations with time in the probabilities of occurrence of some initiating events (e.g. dam failures, floods, etc).

Osborne and Barry (Appendix A) have proposed four individual dose criteria based on various representations of risk as expressed in equation (2-3).

The first criteria involved characterizing the distribution of dose (or consequence) by a single number. Since the integral in equation (2-3) defines the mean dose, it follows that $R = r\bar{H}$ where $\bar{H}$ is the mean dose. R is the statistical expectation of a health effect. As indicated in Figure 2.1(a), R can be compared with a limiting value of risk (R_{ref}) to determine if the individual risk is acceptable.

FIGURE 2·1

CRITERIA FOR LIMITING INDIVIDUAL RISK



The use of a single value (such as the risk of $10^{-5}\ a^{-1}$ suggested by Osborne and Barry) risk criterion is in many ways conceptually appealing. However, use of a single value might not be acceptable since perception of a risk (and ultimately acceptance) depends on the characteristics of that risk. Attitudes towards risk and the willingness to accept risk are highly variable. Factors that influence attitudes include the attractiveness of the benefit(s) to be gained, whether the activity undertaken is voluntary or involuntary, and whether the decision is made by an individual or by a group.

The risk may also be represented by the area under the downward cumulative probability distribution, as shown in Figure 2.1(b). Barry and Osborne refer to the downward cumulative probability distribution as a "tail distribution". For clarity, and consistency with Appendix A, the latter term is used throughout this chapter.

The second criterion is then to compare the risk, as represented by the area under a tail distribution again with a single limiting, or reference value of risk (R_{ref}). As indicated in Figure 2.1(b) a variety of risk curves may meet the criteria, as long as the area under them is less than the criterion value R_{ref}.

Thirdly, one may make a point by point comparison of the estimated tail distribution of dose (or consequence) with a reference tail distribution. The reference distribution would be selected so that its area was equal to the single limiting value (R_{ref}) mentioned previously. Under this criterion, each value of the estimated tail distribution must be less than or equal to the corresponding reference value. This is illustrated in Figure 2.1(c).

The fourth criterion would involve specifying limiting combination(s) of dose (or consequence) and cumulative probability as a means of limiting "risk". As shown on Figure 2.1(d) one might specify a limiting cumulative probability, P_{ref} on some dose H_{ref} (or consequence, rH_{ref}). Thus, the criteria may be met or exceeded regardless of the shape of the curve. Several possible reference (i.e. limiting) consequence/probability combinations may be specified. This criterion does not limit the total individual risk, so that if used it would be to complement one of the other criteria, the intention being to limit the probability of particularly high doses being received.

Barry and Osborne also suggest that an individual who builds, lives and eats on, or adjacent to, the tailings (i.e. an "intruder") may be considered separately and that it is necessary to consider whether the continuing existence of an "intrusion hazard" represents an unacceptable threat to individuals. They suggest that, in practice, the best we can do may be to decide that the probability of intrusion is greater or less than the probability that we seem to accept for intrusion into other artifacts of civilization that may result in similar consequences.

2.2.2 Population Limits

In addition to ensuring that individual risks are acceptable, it is appropriate to manage uranium tailings such that an equitable (optimal) allocation of risks and benefits is obtained. Osborne and Barry (Appendix A) argue that average dose to individuals in a local, regional or even broader area should be kept below a small fraction of the individual dose limit. How much should reasonably be spent, to get to what fraction, averaged over what population, remains a matter of judgement.

The idea of ALARA (an acronym for as low as reasonably achievable, social and economic factors taken into account) has developed in the radiation protection field to permit quantitative optimization of resource allocations. The sum of all the individual radiation doses in a population (termed the "collective dose") is often a useful quantity for ALARA considerations. Collective risk can also be defined in a manner analogous to the collective dose and used in ALARA analysis. The concept of collective risk is equivalent to the number of health effects in a population.

Although simple in concept, ALARA (a type of differential cost-benefit or incremental cost-effectiveness analysis) is difficult to apply to waste management practices. Because of the difficulties in this kind of analysis, the general question of establishing when doses are ALARA has become a very confused issue in discussions of waste management and disposal. In the following section, several such difficulties are discussed and a somewhat more general approach to ALARA is outlined.

2.3 Some Issues in Optimization

Irrespective of the method used for optimization (e.g. ALARA), it is clear that if collective dose or related concepts are to be used, many value judgements are involved. Some of these issues have arisen in actual attempts to optimize and are discussed below.

2.3.1 Discounting Future Dose

One argument is that the detriment to health that may occur in the far future should be valued less than detriment in the near future. This different valuation is irrespective of the certainty with which we can estimate collective dose commitments. Various forms of discounting have been suggested, e.g. an exponential decrease in value with time. One argument for such discounting is that it is unreasonable to expect to have responsibility for civilizations many thousands of years in the future. Morgan (1985) suggests that, "...perhaps the strongest argument for allowing some future discounting in the rate of investment to prevent mortality or morbidity is future technological change which is likely to make greater amounts of safety/dollar invested possible in the future. Of course, acceptability levels may also change... raising the question whether investment rate or safety level is what should be held fixed."

In many instances, these issues are related to time as well. With long-lived radioactive waste, engineered controls for the containment of the waste cannot be guaranteed over times comparable to the half-lives of some of the radionuclides. There will, therefore, be an increasing uncertainty in the predicted release rates from a waste facility as time progresses into the future. Distribution of the released waste over a very long time results in a global distribution that cannot be predicted very accurately for several reasons. We may not have adequate models or appropriate parameters for the long-term processes involved, and there may be changes in the environment - climatic changes for example - or in population size, distribution, and habits. In many instances, estimating what the uncertainties are (i.e. the "error bars" on the estimate of collective dose) may be impossible.

As a consequence of such uncertainties, it may be that no significant difference can be predicted in the estimates of collective doses for different tailings management options. This means that the "preferred" option must be chosen on some other basis.

2.3.2 Very Low Individual Doses

There is considerable confusion in discussions of this issue with ideas on "de minimis", "trivial", or "negligible" doses.

If it is assumed (and it is an assumption) that normal levels of radiation exposures increase the probability of deleterious effects on health, then it follows that successive, relatively small increments in radiation exposures will increase the probability of such effects linearly. In a population, the increased expected number of deleterious effects will be proportional to the summation of all the small increments, i.e. to the collective dose. Hence, if we are considering populations and collective doses of sufficient sizes that we expect at least one deleterious effect to some individual's health, then it can be argued that the number of deleterious effects that will be expected depends only on the size of the collective dose.

Although individual doses (or dose rates) may be considered "trivial" or "de minimis" and ignored, it does not necessarily follow that the total impact can be ignored. One's concern is that if low individual doses associated with any particular source were completely ignored, then the doses from many such sources could add to non-trivial individual doses.

2.3.3 Geographical Distribution of Doses

Long-lived radionuclides from uranium tailings will cross international boundaries. In an attempt to ensure equitable treatment of trans-boundary radioactive pollution, the IAEA (Ahmed and Daw, 1980) has suggested an "international value for dollars per man-sievert" or "international value" as it is often termed to be used in cost-benefit analyses. The intent is that this should be a minimum value for all countries and that if a country chooses to use a higher value for radiation doses within its boundary, then it would use no less a value for doses predicted to be incurred outside its boundary.

This may be an equitable approach to strictly source-related analysis. However, it is difficult to separate "individual-related" consideration from the analysis; that is, not to consider the point of view of individuals in the receiving country.

2.3.4 Low Probability Events

A complicating factor in the use of collective dose for ALARA considerations is the inclusion of low probability, large consequence events in the analysis.

In a situation where an event may result in a very large collective dose but its occurrence may be very improbable, the outcome is either zero - the most probable outcome - or a large collective dose. The expectation value of collective dose is small. As a consequence, the standard deviation of the collective dose is very large - it is inversely proportional to the square root of the probability of the event that resulted in the collective dose. A similar relation would hold for health effects ascribed to the collective dose. For example, if an event with a probability of 10^{-4} of occurring can result in a collective dose of 10^6 man-sieverts to which we would ascribe 10^4 health effects (using the ICRP risk factor), then the expectation would be 1 health effect with a standard deviation of 100. Comparisons on the basis of such quantities are not likely to be very useful. Separate consideration needs to be given to the probabilities of such disruptive events and the collective doses associated with them. A method of incorporating the consequences of low-probability events in an analysis is considered further in Sections 3 and 4 of this report.

2.3.5 The Multicriteria Approach to Optimization

Osborne and Barry (Appendix A) argue that the tailings disposal option that results in the most uniform distribution of collective dose over individuals is preferred. Alternatively, these authors note that other preferences might be established, for example we may prefer an option with the least collective dose. A long list of such preferences can be developed encompassing all radiologically-related factors. We may feel very strongly about some, be fairly neutral to others. The multicriteria approach is simply listing these preferences and their relative weights.

As outlined by Osborne and Barry, the method is:

(a) to select the options to be considered;
(b) to identify all the radiologically-related factors that may indicate a preference for one option over another;
(c) to decide what the preferences are and the relative weights to be given to the preferences in comparisons between pairs of options;
(d) to compare the options on this basis.

Clearly, more judgements are needed than there were in cost-benefit analysis. The major advantage in this approach is that the analysis can be made apparent and debate can focus directly on the factors and weighting without the constraint of attempting to fit all factors into an aggregative analysis.

Such an analysis, concerned with radiologically-related factors, will be only part of an overall analysis that considers other impacts (e.g. social, technical, political, economic, resource commitment) for major projects.

3.0 A CONCEPTUAL APPROACH TO COMBINING RISKS

In this report, risk assessment is the factual (i.e. scientific) use of data to evaluate the effects of a particular situation (in this case, the effects from uranium mill tailings). The science of formal risk assessment is not new and has been used for many years in studies of nuclear power plants and other industrial facilities. Risk assessment is not limited to electrical generation and heavy industry. Insurance companies have for many years been using statistical evaluation of risk to justify car insurance premium differences among different classes of drivers (such as male teenagers, for example).

Morgan (1981) notes that "...risk assessment is at least as much an art as a science..." He identifies a number of potential problems involved in performing and interpreting the results of, a risk assessment. The first problem identified by Morgan is "...a great temptation to use quantitative techniques to get 'the answer'. This is not an appropriate use. Quantitative risk assessment can provide understanding and insight, but it can never capture all the factors, such as quality of life, that are important in a problem, and it should not become a substitute for careful human judgement." We wholeheartedly endorse this view.

This section of the report describes an approach to quantitative risk assessment. In previous sections of the report, risk has been discussed in various terms including expectation of health effects, the product of probability times severity and as a set of triplets expressing the possible risk scenarios, their likelihoods and their consequences. This latter point of view has been applied to the probabilistic risk assessment (PRA) of many nuclear power plants and, in that application, has evolved into a methodology of a very high order of sophistication. The concept is found to be particularly helpful in investigating the (total) risk of uranium mill tailings. The ideas presented in this section are based on the discussions in Appendix B and the work of Kaplan and Garrick (1981).

3.1 Quantitative Definition of Risk

As discussed in Chapter 2, the concept of risk can be expressed as a triplet.

$$<s_i,l_i,x_i> \qquad (3\text{-}1)$$

where s_i is a name or description of a "scenario" i.e. an answer to "what can happen?"; l_i is the likelihood of that scenario; and x_i is a "damage index". In simple terms x_i is a measure of the consequences of the scenario. (If desired, x_i can actually be a vector of damage indices, giving different aspects or components of the consequences, e.g. damage to people (dose perhaps), to property, to environment, to wildlife, etc.).

Using brace brackets, $\} \{$, to denote "set of" and R to denote "risk", one may write:

$$R = \}<s_i,l_i,x_i>\{ \qquad (3\text{-}2)$$

That is, for analytic purposes, the risk (R) is the set of triplets defined by equation (3-2) in the sense that this set answers our questions. It tells us everything we wanted to know about risk but were perhaps unsure how to ask. It does this of course, if, and only if, the set is "complete", that is contains all possible scenarios. So let us discuss this issue briefly.

3.2 Defining Scenarios

Certain critics of quantitative risk analysis have argued that any list of scenarios, as in equation (3-2), developed in a risk study is necessarily finite whereas the actual list is infinite. They use this argument to devalue the risk study, no matter how detailed and thorough, saying that they are not concerned with the scenarios on the list, but with those not on the list.

This argument has both merits and demerits. Note that when we define a "scenario" (or combination of events) with some finite set of words, we are actually defining a whole category of scenarios. Thus, for example, suppose we define scenario #2 (S_2)as:

$$S_2 = \text{"the pipe breaks"} \qquad (3\text{-}3)$$

The pipe can break in many different ways, in many different places, at different times and under different circumstances. Thus the definition given by equation (3-3) actually encompasses this whole category of scenarios.

If we wished to increase the level of detail in our risk model, we could define smaller categories, e.g. "longitudinal pipe break", "Guillotine break", etc. Each of these statements defines a smaller category but it is still a category. This is true however elaborately we define the scenario. Apostolakis (1978) cautions that "one need not carry the analysis too far and thus run the risk of complete separation from reality."

Observing, therefore, that all our scenarios are actually scenario categories, we can choose our words carefully when defining the s_i so as to make the set of categories (logically) complete.

Consider, for example, the uncontrolled (or at least unsatisfactorily controlled) release of waterborne radionuclides from an operational tailings impoundment. The list could have only one scenario:

$$S_1 = \text{"unacceptable release occurs"} \qquad (3\text{-}4)$$

However, while the list is logically complete it is not of much use. To analyse the "unacceptable release" we define smaller categories:

$$S_1 = \begin{array}{l}\text{"operator or equipment failure}\\ \text{in treatment system leading to}\\ \text{unacceptable release"}\end{array} \qquad (3\text{-}5)$$

$$S_2 = \text{"failure of tailings impoundment leading to unacceptable release"} \qquad (3\text{-}6)$$

These two scenarios also constitute a logically complete list. However, both S_1 and S_2 can be further divided into smaller categories; for example, "Operator or equipment failure" can be expected to include failure due to mechanical malfunction (of any type leading to unacceptable release), failure due to loss of electrical power and operator failure (of any type leading to unacceptable release). Completeness can be maintained at each level of refinement. The notion of completeness as used here is analogous to the idea of "coherence" described previously by Apostalakis (1978).

3.3 Expressing Likelihood

The idea of likelihood can be expressed in several different ways, appropriate to different situations. For a first example, suppose the scenario, s_i, in question is the failure of the brakes in a certain category of large truck; a partial failure is considered to be a failure. Thus, each time the brakes are asked for (demanded), they either "work" or "fail".

Since there are many thousands of such demands each year, and a substantial number of failures, it is convenient to think about likelihood in terms of the "frequency", f_i, of brake failure, i.e. in terms of the number of failures per demand.

Similarly, with a piece of equipment that operates continuously, say a pump, we would express likelihood as a frequency measured in failures per unit time.

Thus, when we have a repetitive situation, the idea of likelihood is expressed as a frequency.

$$l_i \rightarrow f_i, \text{ (failures per demand or failures per unit time)} \qquad (3\text{-}7)$$

Now, for a non-repetitive example, suppose we are contemplating a manned flight to Mars. This being a "one shot" situation, no frequency is involved. Here the appropriate expression of "likelihood" is "confidence". We ask, "How confident are we that the crew will return safely?" (i.e. "How strongly do we believe that the crew will return safely?"). Thus, in this non-repetitive situation, the idea of likelihood is expressed as probability.

$$l_i \rightarrow p_i \qquad (3\text{-}8)$$

Returning now, for the next example to the case of brake failure, we may find ourselves in the following situation: Although the failure frequency is a well defined number, since there are many failures and very many demands, it may be that we do not know what the number is. It may be, for example, that the records have not been well kept. Thus, we are in the position where we know f_i exists but we are uncertain about what its value is. We have only our own experience to go on, along with such data as we can locate, and possibly also the opinions of experts in the trucking industry. On this basis, we may express our state of knowledge in the form of a probability distribution, p_i, against f_i.

Thus, in this case, likelihood is expressed as a "probability of frequency" distribution.

$$l_i \rightarrow p_i(f_i) \qquad (3\text{-}9)$$

Equation (3-9) together with equations (3-7) and (3-8) thus provide three different formats for expressing the idea of likelihood.

For the present purposes the interpretation of likelihood as a subjective probability (for the occurrence of a particular scenario) is most useful.

3.4 Expressing Consequences

In our basic definition of risk, equations (3-1) and (3-2), x_i is referred to as a "damage index" which measures the consequences of the ith scenario. Actually, in most cases of risk analysis, we find that there are different types of damage that can occur. There are damages to people, to property, to environment, wildlife, reputation, etc. In concept, each of these could be measured by its own damage index. We can therefore, think of the x_i in equations (3-1) and (3-2) as being actually a vector of damage indices, with each component measuring a different type of damage. Sometimes it is appropriate also to let the x_i's be functions of time. This is the situation, as we shall see, in the case of a tailings pile where $x_i(t)$ could represent, for example, the entire time history of leakage of potentially hazardous materials from the pile.

This assignment of damage index values completes the basic formalism required for our risk analysis (i.e. we have defined our triplets). The triplets can then be presented either as "event trees" or as "risk curves". Both are illustrated in Chapter 4 using the probabilistic analysis of a reference uranium tailings facility as an example. The set of triplets, the event tree(s), and the totality of risk curves are equally valid, alternative representations of the total risk, R.

4.0 APPLICATION TO CANADIAN URANIUM MILL TAILINGS

4.1 Description of the Reference Facility

To demonstrate the techniques discussed in Chapter 3, a hypothetical reference tailings site was defined. The characteristics of this site, and the mathematical models used to describe its effects on the environments, were adopted from an earlier NUTP project (SENES 1984). The reference facility was defined to reflect the major environmental features and environmental transport pathways pertinent to tailings management on the Canadian Precambrian Shield. The characteristics of this facility are illustrated in Figure 4.1.

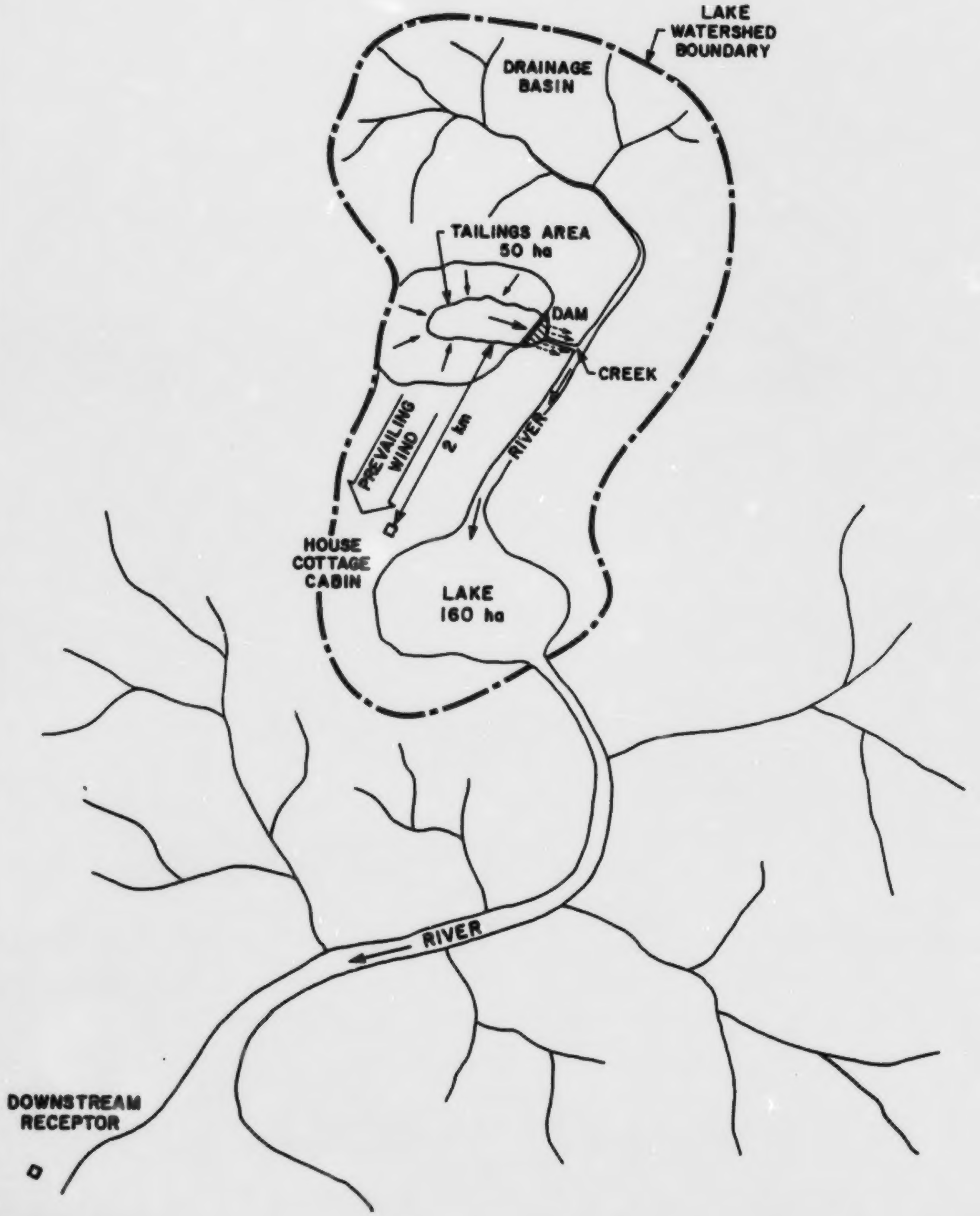
The tailings disposal site was taken to occupy a natural depression formed within the upper reach of a valley, that is, a land/shallow-water type site. The tailings were considered to be contained behind a conventional dam constructed across the low point. The reference tailings site was defined to have a surface area of 50 ha and an average tailings depth of 10 m, for a total volume of 5×10^6 m^3. The natural depression containing the tailings was assumed to be 150 ha in area (including the tailings).

The reference tailings characteristics were assumed to represent those resulting from the acid leaching of low-grade pyritic uranium ore containing around 0.1% uranium. Tailings were assumed to contain 4 to 5% of the original uranium (i.e. between 95 and 96% of the uranium was extracted from the tailings during the milling process). Essentially all of the original radium in the ore typically remains with the tailings material. The radium concentration was selected to range between 5.0 and 15 Bq/g.

The effects of the tailings mass on the environment and on the hypothetical human receptors were determined using a set of environmental pathways models. Radionuclides modelled included radon gas release from the tailings surface, radium dispersal with windblown particulates and dissolved radium transport in surface water. The exposure pathways considered are shown schematically

FIGURE 4·1

SCHEMATIC ILLUSTRATION
OF WATERSHED SETTING
FOR THE REFERENCE TAILINGS SITE


LAKE
WATERSHED
BOUNDARY
DRAINAGE
BASIN
TAILINGS AREA
50 ha
DAM
CREEK
RIVER
PREVAILING
WIND
2 km
HOUSE
COTTAGE
CABIN
LAKE
160 ha
RIVER
DOWNSTREAM
RECEPTOR

below, and described in some detail in Appendix C.

- radon exhalation → air dispersion → inhalation
- wind erosion of tailings → air dispersion → deposition on vegetables → ingestion
  - deposition on vegetables ↓ transfer to meat → ingestion
  - air dispersion → inhalation
- seepage → dilution in river and lake water → drinking water ingestion
  - dilution in river and lake water → transfer to fish → ingestion

The number of pathways were limited to make the exercise tractable. However, it is worth noting that our experience suggests that even this restricted set of pathways illustrates all the salient features of pathways modelling and indeed is likely to account for the majority of the potential radiological health effects.

These pathways were modified for one receptor (as will be described in Section 4.3).

4.2 Events Considered

The basic "events" considered in this study are listed in Table 4.1 along with an estimate of the annual probability of their occurrence and the expected number of times the event will occur in the thousand year modelling period (i.e. long-term average). It should be noted that the effects calculated for each event assume that no human action is taken to mitigate the consequences

Table 4.1

Probability of Natural Events

Event	Probability Per Year[1]	Probability of Non-occurrence in 1000 Years[3]	Probability of One or More Occurrences in 1000 Years[4]
Null[2]	9.98×10^{-1}	na	na
Forest Fire	2×10^{-3}	0.14	0.86
Drought	1×10^{-4}	0.90	0.10
Precipitation	5×10^{-5}	0.95	0.05

Notes

1. Subjective probability based on our current state of knowledge
2. Obtained by difference: Pr (Null) = 1 - [Pr (forest fire) + Pr (drought) + Pr (precipitation)]
3. $(1 - \text{annual probability of event})^{1000}$
4. Obtained by difference: (1 - probability of non-occurrence)

of any of the events. Thus, all results to follow are appropriate for a "walk-away" or "one time solution" tailings management strategy. The analysis would require modifications for other tailings management strategies. There are several further assumptions worth noting. First, all events are assumed to be independent of one another, and to exhibit no temporal correlation. That is, the occurrence of any event in any year does not affect the subsequent occurrence of any other event. Finally, it was assumed that there were no significant climatic changes over the 1000 year modelling period.

(i) The Null Event

The term "Null" event refers to the basic tailings scenario which, in the absence of one or more "unusual" events, is assumed to propagate through time in a more or less well-behaved fashion. Since the pathways models simulate a quasi steady-state condition, the effects calculated in any year are equally representative of any other year. Thus, no time dependency is incorporated in modelling the null event. The tailings are assumed to be 90% vegetated and to experience a constant rate of erosion.

(ii) Forest Fire

The effect of a forest fire is assumed to be a temporary reduction of vegetative cover with an attendant increase in windborne particulates and water erosion. For the present analysis this event is modelled as a reduction in vegetative cover from 90% (Null case) to 50% with natural revegetation taking place over a period of 10 years.

(iii) Drought

An extended period of severe drought is assumed to result in a substantial reduction in vegetative cover (to 10% cover). Following the drought there is a gradual recovery of vegetative cover over a 20 year period. During the period of reduced cover there will be increased wind and water erosion. During the drought the tailings moisture is reduced, leading to enhanced radon exhalation.

(iv) Precipitation/Containment Failure (Flood)

This event is actually the combination of two events; namely a major precipitation event (flood) leading to a failure of the tailings dam. A substantial fraction (10%) of the impounded tailings mass is assumed to be released to the lake. This results in an immediate increase in dissolved radium concentration in the lake; which is diluted relatively rapidly as a function of lake residence time. There will also be long-term leaching of radium from the redistributed tailings solids on the lake bottom. Radium flux will return to null event levels in approximately 100 years, as the lake bottom becomes covered with sediment. This event also results in increased wind and water erosion from the remaining, devegetated tailings mass. Revegetation, from the post-event 10% cover to the null event level (90% cover) is assumed to occur over a 20 year period.

4.3 Receptors Considered

For the purposes of this study, three human receptors were modelled. The characteristics of each are outlined below and explained in more detail in Appendix C.

(i) Reference Receptor

The reference receptor is assumed to be an adult male who lives year-round in a cabin on the lake, as shown on Figure 4.1, some 2 km downstream of the reference tailings site. This individual is assumed to live off the land, deriving approximately 50 percent of his food supply from local sources: eating some vegetables and berries grown or harvested near the residence, eating some fish taken from the lake, and eating some caribou hunted in the immediate area. All drinking water is taken from the lake and consumed directly without special treatment for radium removal.

(ii) Downstream Receptor

The downstream receptor was assumed to live farther away from the tailings, and to have more moderate living habits than the reference receptor. While the reference receptor might represent a hunter/trapper, the downstream receptor is likely more representative of the average resident of a small mining town. This receptor was assumed to derive all his drinking water from local supplies (in this case; a river), but to consume less local food than the reference receptor.

(iii) Tailings Intruder

Since the possibility exists that some individual(s) may construct dwellings on the tailings at some future time, such a receptor was modelled. The tailings intruder was assumed to reside in a house having an unfinished basement partially below the tailings surface. He was assumed to hunt, fish and trap locally and to have a small vegetable garden on the tailings. It was further assumed that water obtained from any well sunk into the tailings would not be potable; hence, the intruder's water would be drawn from the nearby river. The primary exposure pathways for this receptor were considered to be external radiation (while outside) and radon inhalation while indoors. The pathways models were altered to reflect these changes.

4.4 Results

4.4.1 Consequences of the Events

A variety of consequences, for the events and receptors just described were calculated by evaluating the appropriate models using a probabilistic analysis computer program (RANSIM) developed by SENES Consultants Limited (SENES, 1985). Consequence predictions were calculated using RANSIM for a total of 200 simple random trials. The results of such probabilistic analyses can be graphically displayed as frequency distributions (histograms) of calculated results (see, for example, Figure 4.3). Such distributions can be summarized by their various statistical attributes (moments, quantiles, etc.). In this study, the arithmetic mean and standard deviations were chosen to represent the distributions of calculated results. The predicted consequences of each of the events are summarized in Table 4.2.

The time dependency of consequences due to major natural events such as floods or forest fires was accounted for explicitly in the mathematical simulations. This is illustrated in Figure 4.2, which shows the time dependent behaviour of total annual dose to the reference receptor for a single flood event. The points plotted represent the arithmetic mean values, at each time, of 200 random trials. Following the event, the dose rises rapidly and then returns to pre-event (baseline) levels in approximately 100 years.

Because of such time-varying behaviour, and since several receptors were modelled, a number of consequences were calculated for each event. These consequences are summarized in Table 4.2 and discussed below.

(i) Maximum Annual Dose

The maximum annual dose to a receptor was assumed to occur in the first year following any episodic event. Since the models, as formulated, were designed to calculate an annual dose, no time dependency was required for these calculations. That is, the probabilistic simulations were performed for a single time period (1 year). The "maximum annual dose" for both the null event (reference receptor) and the intruder receptor is assumed to represent such consequences at any time.

As mentioned previously, the probabilistic results can be displayed graphically as histograms. As an example, the frequency distributions of maximum annual dose to the reference receptor, for both the null event and the flood event are presented in Figure 4.3 (a and b). Note that the mean value and standard deviation for each effect are summarized in the appropriate column in Table 4.2. It is possible to generate such histograms for all calculated effects. However, only the summary statistics (e.g. mean and

TABLE 4.2

SUMMARY OF RESULTS

	CONSEQUENCE				
EVENT	Max. Annual Dose to Ref. Receptor (Sv/yr)	50 Year Average Annual Dose to Ref. Receptor (Sv/yr)	Cumulative Dose (Sv/time) to Downstream Receptor	Cumulative Ra Flux to Water (Bq/time)	Dose to Intruder (Sv/yr)
NULL	$.989 \times 10^{-4}$* $(.569 \times 10^{-4})$**	$.964 \times 10^{-4}$ $(.399 \times 10^{-4})$	$.097 \times 10^{-4}$ Sv/yr $(.049 \times 10^{-4})$	0.024×10^{11} Bq/yr $(.00846 \times 10^{11})$	3.24×10^{-1} (1.33×10^{-1})
FIRE	1.52×10^{-4} $(.740 \times 10^{-4})$	$.996 \times 10^{-4}$ $(.412 \times 10^{-4})$	2.06×10^{-4} Sv/20 yr (1.03×10^{-4})	$.517 \times 10^{11}$ Bq/20 yr $(.170 \times 10^{11})$	
DROUGHT	1.78×10^{-4} $(.861 \times 10^{-4})$	1.03×10^{-4} $(.428 \times 10^{-4})$	4.18×10^{-4} Sv/40 yr (2.07×10^{-4})	1.01×10^{11} Bq/40 yr $(.328 \times 10^{11})$	
FLOOD	8.54×10^{-4} (4.71×10^{-4})	2.02×10^{-4} (1.08×10^{-4})	14.6×10^{-4} Sv/100 yr (7.52×10^{-4})	2.70×10^{11} Bq/100 yr $(.864 \times 10^{11})$	

* mean values of 200 trials

** standard deviation of 200 trials

FIGURE 4·2

TIME VARYING BEHAVIOR: MAXIMUM ANNUAL DOSE TO REFERENCE RECEPTOR (FLOOD EVENT)

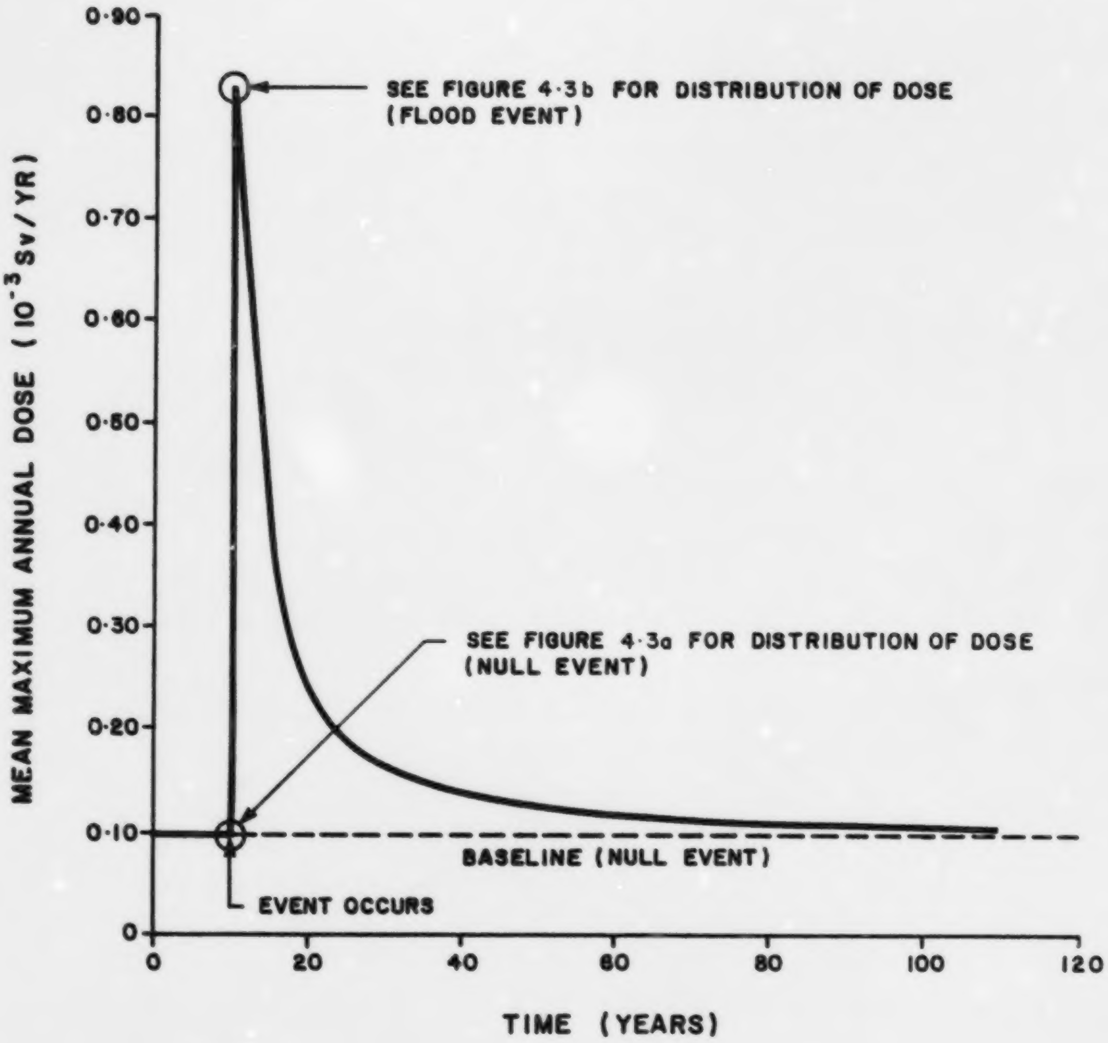


FIGURE 4·3a

MAXIMUM ANNUAL DOSE TO REFERENCE RECEPTOR (NULL EVENT)

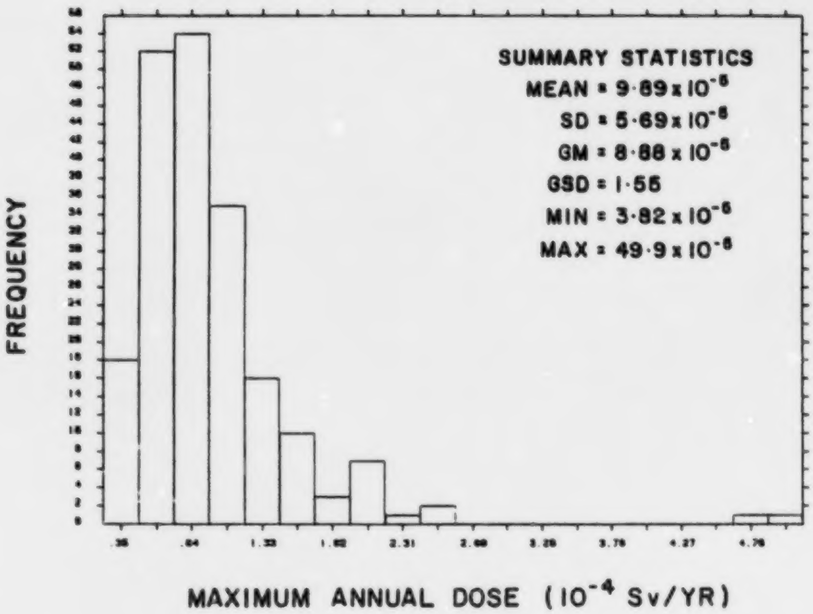
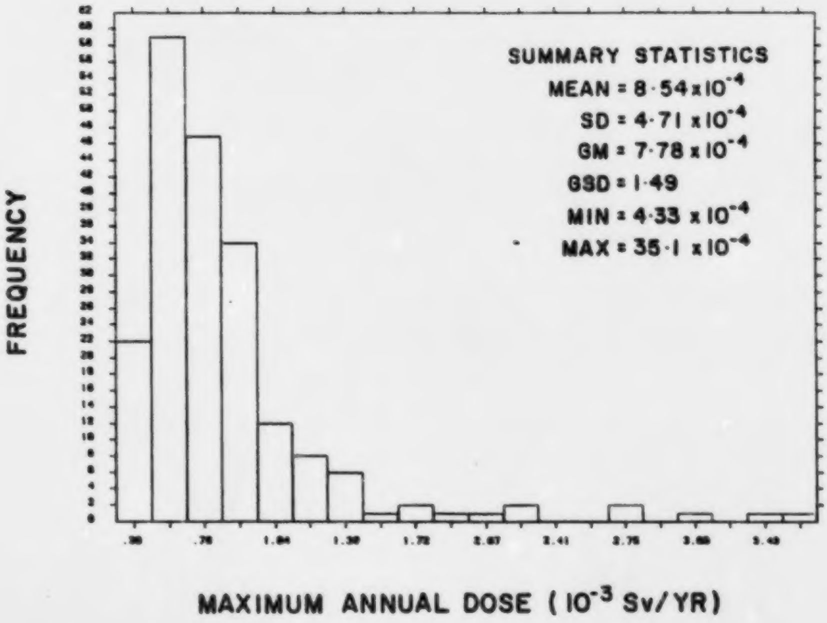


FIGURE 4·3b

MAXIMUM ANNUAL DOSE TO REFERENCE RECEPTOR (FLOOD EVENT)



standard deviation) of each are presented in the table and used in further analysis in this report. More detailed results are presented in Appendix C of this report.

The maximum annual dose results indicate that the fire and drought events increase the maximum annual dose by about 1-1/2 times from the "null" event dose while the flood event increases it by approximately a factor of eight. The dose to the intruder is more than three orders of magnitude greater than that to the reference receptor.

(ii) 50 Year Average Annual Dose

The maximum "lifetime" dose to the reference individual will occur in the decades following any natural event. For illustrative purposes, an average annual dose to the reference receptor for the 50 years following an event was calculated. This consequence then, represents an approximation to the maximum average annual dose to the reference receptor over a lifetime, as a result of an event. It was calculated by performing (200) probabilistic simulations, each representing a 50 year period. The 50 year average annual values were determined for each simulation. Again, detailed results are presented in Appendix C, and summarized in Table 4.2.

The 50 year average annual dose to the reference receptor for the null event should equal the maximum annual dose. The differences noted between the results on Table 4.2 are due to the random nature of the simulation and are fully expected.

A comparison of the maximum annual and 50 year average annual doses gives the impression that the episodic fire and drought events produce only a marginal increase in dose to the reference receptor. This occurs because these events affect the system for only 10 to 20 years, with the majority of the effects concentrated in the first 5 years following the event.

(iii) Cumulative Consequences

Neither of the previous two consequences indicates the total (cumulative) effect of any event over time. Since the downstream receptor is considered more representative of the surrounding population, and since a cumulative population dose may be of interest, the cumulative doses to the downstream receptor were calculated for the duration of the various events. These were determined by summing the annual downstream receptor doses over the time periods indicated below. This consequence assumes that a downstream receptor is present (with replacement) for the duration of any event. Duration of events (i.e. the time required to return (at least nearly) to pre-event conditions were modelled as:

NULL	1 year
FIRE	20 years
DROUGHT	40 years
FLOOD	100 years

Cumulative downstream receptor dose was used in further calculations to estimate a cumulative population dose. Cumulative fluxes of radium to air and water and radon to air were also calculated. The cumulative dose to the downstream receptor, and cumulative radium flux to surface water are summarized in Table 4.2. See Appendix C for more detailed results.

4.4.2 Construction of Risk Curves

Much of the information presented in the preceding sections can be summarized using an "event-tree". Details regarding the construction of an event tree for the present example can be found in Appendix B. An event tree, for the events considered in this study (excluding intrusion), is presented in Figure 4.4.

The various combinations of events considered (known as scenarios) are shown on the left side of Figure 4.4. In this example, 20 combinations of events

FIGURE 4·4

RISK EVENT TREE
(EXCLUDING INTRUSION)

EVENTS			Scenario		DAMAGE INDICES			
Precipitation	Drought	Forest Fires	Number	Probability	Max. Annual Dose (Sv/yr)	Max 50 yr Avg. Annual Dose (Sv/yr)	Cumulative (1000 yr) Population Dose (Sv)	Cumulative Radium Flux to Surface Water (Bq)
.951[a]	.905	.135	1	.116	$.989x10^{-4}$	$.964x10^{-4}$	$9.70\ x10^{1}$	$2.4\ x10^{12}$
		(.27)(1)[c]	2	.232	$1.52x10^{-4}$	$.996x10^{-4}$	$9.71\ x10^{1}$	$2.40\ x10^{12}$
		(.27)(2)	3	.232	↓	↓	$9.72\ x10^{1}$	$2.41\ x10^{12}$
		(.18)(3)	4	.155	↓	↓	$9.74\ x10^{1}$	$2.41\ x10^{12}$
		(.145)(4+)[d]	5	.125	↓	↓	$9.75\ x10^{1}$	$2.42\ x10^{12}$
	(.095)(1+)	.135	6	.012	$1.78x10^{-4}$	$1.03x10^{-4}$	$9.73\ x10^{1}$	$2.41\ x10^{12}$
		(.27)(1)	7	.024	↓	↓	$9.74\ x10^{1}$	$2.41\ x10^{12}$
		(.27)(2)	8	.024	↓	↓	$9.75\ x10^{1}$	$2.41\ x10^{12}$
		(.18)(3)	9	.016	↓	↓	$9.77\ x10^{1}$	$2.42\ x10^{12}$
		(.145)(4+)	10	.013	↓	↓	$9.78\ x10^{1}$	$2.42\ x10^{12}$
(.049)[b](1+)	.905	.135	11	.006	$8.54x10^{-4}$	$2.02x10^{-4}$	$1.02\ x10^{2}$	$2.43\ x10^{12}$
		(.27)(1)	12	.012	↓	↓	1.02 x102	$2.43\ x10^{12}$
		(.27)(2)	13	.012	↓	↓	$1.02\ x10^{2}$	$2.44\ x10^{12}$
		(.18)(3)	14	.008	↓	↓	$1.02\ x10^{2}$	$2.44\ x10^{12}$
		(.145)(4+)	15	.006	↓	↓	$1.02\ x10^{2}$	$2.44\ x10^{12}$
	(.095)(1+)	.135	16	.0006	↓	↓	$1.02\ x10^{2}$	$2.44\ x10^{12}$
		(.27)(1)	17	.0013	↓	↓	$1.02\ x10^{2}$	$2.44\ x10^{12}$
		(.27)(2)	18	.0013	↓	↓	$1.02\ x10^{2}$	$2.44\ x10^{12}$
		(.18)(3)	19	.0008	↓	↓	$1.03\ x10^{2}$	$2.45\ x10^{12}$
		(.145)(4+)	20	.0007	↓	↓	$1.03\ x10^{2}$	$2.23\ x10^{12}$

Notes

a) p = probability of event not occurring in 1000 years
b) (p) = probability of event occurring in 1000 years
c) (n) = n events
d) (n+) = n or more events

(i.e. scenarios) are presented. As discussed earlier, each scenario actually represents a whole class of scenarios. The probabilities noted on each line segment represent either the probabilities of the indicated events not occurring or (in brackets) the probability of the events occurring in the 1000 year modelling period. Even the small number of events considered in this study can produce an extremely large number of scenarios, many with very low probabilities of occurrence. To keep the example tractable, the very low probability scenarios, generally consisting of multiple event occurrences, were lumped together. Thus in some scenarios, multiple events are considered implicitly (indicated as (1+)) or explicitly (e.g. (2), (3), (4+)).

By tracing combinations of events, and multiplying the event probabilities, scenario probabilities can be determined. Each scenario has associated with it a series of damage indices. Four damage indices were considered in this study, but many more and/or different indices could be used.

Note that the probabilities of scenarios shown on Figure 4.4 sum to one, and, in this sense, are complete. This does not ensure that the list of events used to construct the scenarios is also logically complete. Both aspects of completeness (i.e. events and scenarios) would need to be reviewed in any analysis of a specific site.

An example may best illustrate how to interpret the information presented on the event tree. Consider a scenario involving no precitation event (flood), one drought and three forest fires in a 1000 year period. The probability of such a scenario (scenario #9 in Figure 4.4) is equal to:

$$.951 * .095 * .18 \approx 0.016$$

The maximum annual dose associated with this scenario is equal to that resulting from a drought (see also Table 4.2) as is the maximum 50 year average annual dose. The cumulative population dose was calculated using the downstream receptor results.

The damage indices all employ the results summarized on Table 4.2 (which, in turn, represent a summary of the many frequency distributions). Thus, in this demonstration, arithmetic mean values of consequences were used to determine damage indices. Note also that Table 4.2 contains estimates of the uncertainties associated with the calculated results. For ease of presentation, these uncertainties are not duplicated in subsequent results. The information presented here is sufficient to allow the interested reader to propagate the uncertainties through subsequent analysis. Other descriptors of the output frequency distributions (such as geometric mean, 10th, 50th or 90th percentiles) could also be used. The first two damage indices, maximum annual dose (to the reference receptor) and 50 year average annual dose (to the reference receptor) are taken directly from Table 4.2. The cumulative damage indices (population dose and radium flux to surface water) are somewhat more involved.

The cumulative damage indices indicate the consequence of the scenarios over the entire 1000 year modelling period. For example, the cumulative radium flux to water for the scenario mentioned earlier (scenario #9) was calculated as shown below.

1 drought $= 1.01 \times 10^{11}$ Bq/40 years

3 forest fires $= 3*(.517 \times 10^{11}$ Bq/20 years)
$= 1.55 \times 10^{11}$ Bq/60 years

900 years of null event $= 900*(.024 \times 10^{11}$ Bq/yr)
$= 2.16 \times 10^{12}$ Bq/900 years

cumulative radium flux $\approx 2.42 \times 10^{12}$ Bq/1000 years

The 1000 year cumulative population dose was calculated in a similar manner, assuming a population consisting of 10,000 downstream receptors. For those scenarios involving intrusion, 5 intruders residing on the tailings for 50 years were added to the population. Further details regarding the calculation of these damage indices are presented in Appendix B.

It should be noted that the cumulative radium fluxes differ very little between scenarios. In fact, the only differences noted are in the third and fourth significant digits. This occurs primarily because the events considered in the study are of relatively short duration relative to the 1000 year modelling period, and thus are overshadowed by the many years of null event conditions in a cumulative consequence calculation.

The cumulative population dose takes on essentially two discrete values, corresponding to those scenarios including floods and those excluding floods. The relatively short duration, and minimal effects of forest fire and drought events are again reflected in the negligible differences between many of the cumulative (1000 year) population doses.

A risk curve can be constructed for each damage index, using the procedure outlined in Appendix B. Such a risk curve, with maximum annual dose to the reference receptor as consequence is shown in Figure 4.5. The curve summarizes the risk (in this case the risk being maximum mean annual dose) to the reference receptor from all combinations of events for the 1000 year modelling period. It can be used to provide an estimate of the probability of exceeding a given maximum annual dose for any scenario. For instance the probability of a maximum annual dose to the reference receptor being greater than 5×10^{-4} Sv/yr is approximately 0.05.

The probabilistic nature of the original analysis also allows the construction of error bars or confidence bands on these risk curves (as illustrated on Figure 4.5). For each scenario on the event tree (Figure 4.4), 2 new damage indices were calculated, corresponding to the mean maximum annual dose plus or minus 2 standard deviations. (The arithmetic mean ± 2 standard deviations accounts for 95% of the area under a (normal) probability density curve.) Plotted on the same figure as the mean maximum annual dose they produce the shaded confidence region shown.

A risk curve (Figure 4.6) was also constructed using cumulative population dose as the damage index. Population here refers to the downstream receptors and the tailings intruder as described previously. Information necessary to construct this curve is summarized in the larger event tree in Appendix B (Figure B.2). The left side of the curve in Figure 4.6 (i.e. cumulative dose less than 102 Sv) is due to those events involving no intrusion. The small step in the middle of the figure (near dose 100 Sv) represents the effects of flood events. The right side of the curve results from those scenarios which include intrusion, and again, the small step at the far left is due to the effects of floods. Several other risk curves are presented in Appendix B.

The event tree (e.g. Figure 4.4) represents the total risk from uranium mill tailings, at least insofar as we have chosen to examine it. The totality of risk curves, one curve for each consequence, also represents the risk from uranium mill tailings, but in a different format. As mentioned earlier each scenario on the event tree actually represents a whole class of scenarios. Thus it is possible to expand the event tree. Similarly, it is easy to envisage additional consequences which one could calculate; for example, the annual average radon-222 concentration at the nearest receptor or 50th percentile of maximum annual dose. Whether or not such additional effort would help one to determine whether or not the "risk" is acceptable is a different question. A risk assessment, no matter how detailed, while providing much insight into the problem, does not relieve the decision maker from actually making a decision - in this case whether or not the tailings are sufficiently safe.

FIGURE 4·5

RISK CONSEQUENCE CURVE
MAXIMUM ANNUAL DOSE TO REFERENCE RECEPTOR

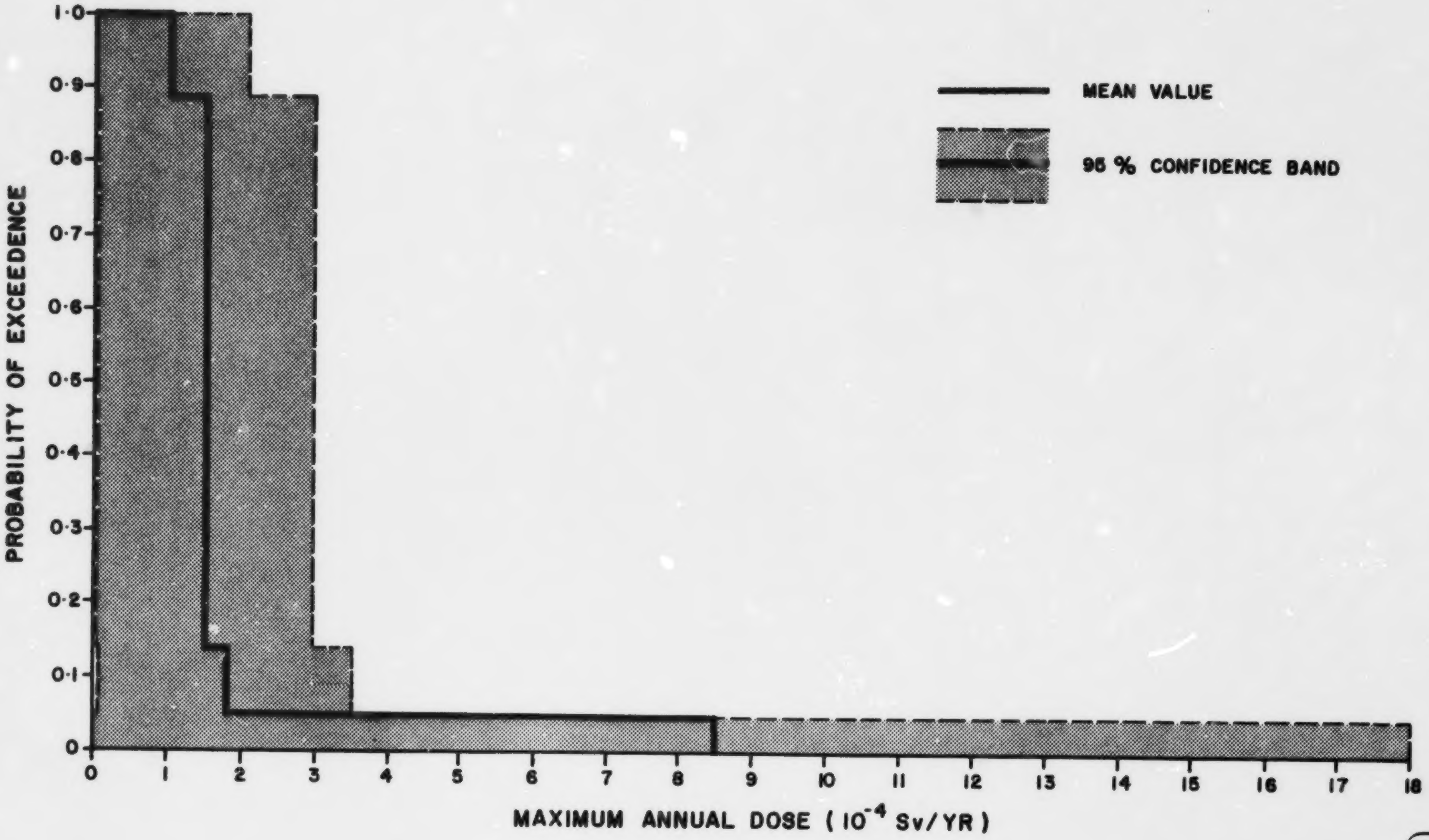
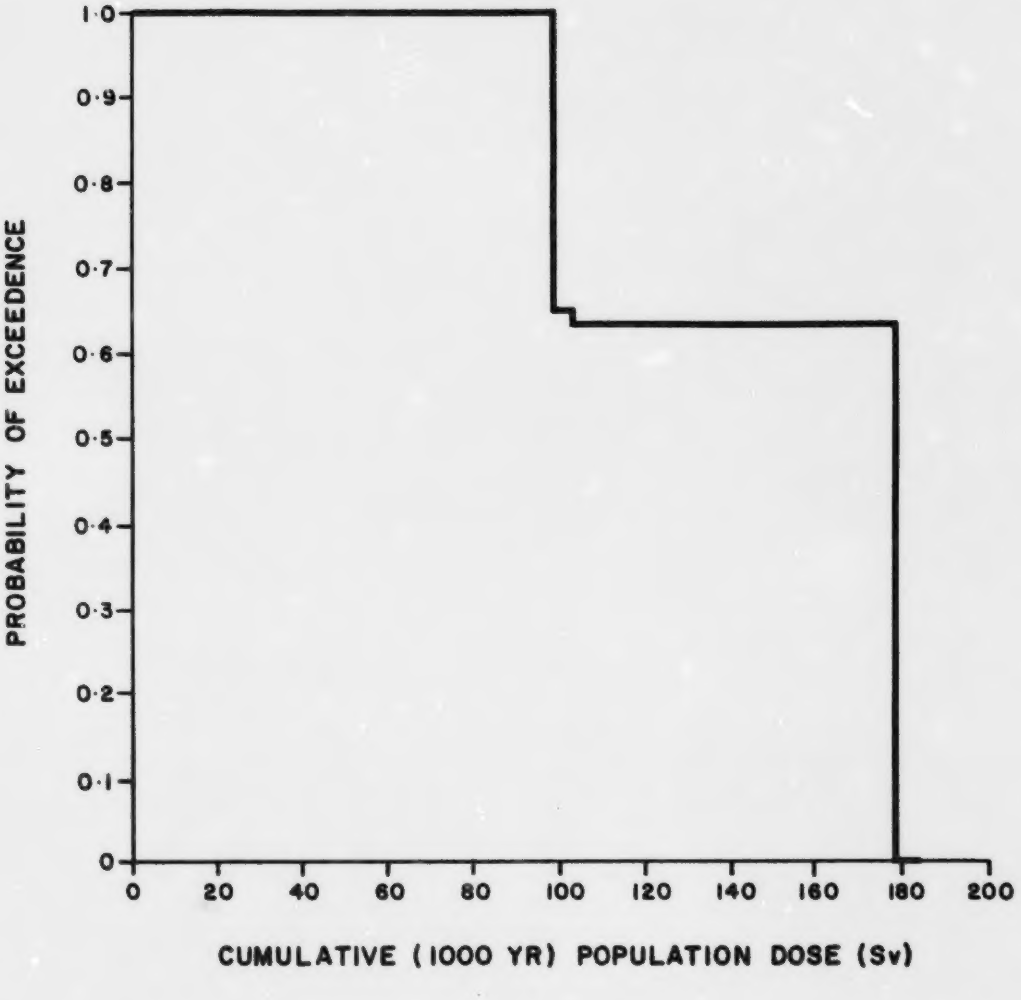


FIGURE 4·6

RISK CONSEQUENCE CURVE CUMULATIVE (1000 YR) POPULATION DOSE (INCLUDING INTRUDER)



5.0 PRINCIPAL OBSERVATIONS AND RECOMMENDATIONS

5.1 Principal Observations

In assessing the effects of uranium mill tailings it is clear that one must ensure that individuals are protected sufficiently. In practice, this requires that the maximum risk to the most highly exposed individual(s) be sufficiently small. (It is not clear, however, just exactly what sufficiently small is.) Given that the most exposed individual is suitably protected, optimization procedures such as ALARA or a generalized multi-attribute analysis may be used to ensure that resources, benefits and consequences are equitably distributed. These considerations may help one choose between alternative tailings management options.

In the report (and Appendix A) several risk-based criteria to ensure individual and collective protection, are discussed, as are various factors involved in comparing tailings management options. However, in our view there is no single criterion which can be used to judge whether or not risk is sufficiently small. It is likely that many measures of harm will have to be calculated and provided to the decision maker in an understandable form.

The report also sets out a risk assessment methodology which is based on defining risk as a set of triplets. The triplets are answers to the set of questions: what can happen? how likely is it? and, if it happens, what are its consequences? Individual events can be structured into an event tree which includes information regarding the likelihood and consequences of the various combinations of events (known as scenarios). Alternatively, the same information can be presented in terms of risk curves where the scale of the horizontal axis is consequence (e.g. maximum annual dose) and the vertical axis is the probability that a particular consequence will be exceeded. The risk assessment methodology has been demonstrated using the results of a probabilistic analysis of a reference uranium tailings site.

5.2 Recommendations

It is our view that the risk assessment methodology described and demonstrated in this report is appropriate for the analysis of risks arising from uranium mill tailings. However, to further demonstrate its usefulness, the technique should be applied to an actual tailings site and to alternative tailings management options. Such a project would require considerable effort to characterize the tailings site (if not already done), the natural episodic events which have the potential to affect the site and the alternative tailings management options. One possible way to expedite such an exploratory risk assessment would be to apply the methods of the report to a site which has already been closed out and for which basic data are readily available. Potential candidates for such a study would include the Beaverlodge and Gunnar sites in northern Saskatchewan, the Lacnor site near Elliot Lake and the site in Madawaska, Ontario.

A second area for continued study is the further incorporation of time dependency into a risk analysis. In the present study, the episodic events were explicitly treated as time dependent, while the base case (null event) was assumed to be in a quasi-steady state. The latter aspect is somewhat unrealistic, since the physical and chemical behaviour of the tailings might well be expected to change considerably with time. This aspect and other considerations of time could be examined in more detail than allowed by constraints of this study.

The final recommendation involves the interpretation and presentation of the results of a risk assessment and their use by a decision maker. It is not yet clear whether or not the multitude of data available from a probabilistic risk assessment, will simplify or complicate the decision making process. Further attention should be given to determining which consequence(s) of a probabilistic analysis, and which attribute(s) of the calculated frequency distributions should be used in a risk analysis. Also the incorporation of the risk assessment results (i.e. event-tree(s), risk curve(s)) into a decision-making framework should be investigated. Such investigations might consider the various qualitative criteria, such as multi-attribute analysis, mentioned in this report.

REFERENCES

Ahmed, J. U. and Daw, H. T., 1980. "Cost-Benefit Analysis and Radiation Protection." International Atomic Energy Agency Bulletin, Vol. 22, No. 5/6, pp. 13-22, October.

Apostolakis, G., 1978. "Probability and Risk Assessment: The Subjectivistic Viewpoint and Some Suggestions." Nuclear Safety, Vol. 19, No. 3, pp. 305-315.

Beninson, D., and Lindell, B., 1981. "Critical Views on the Application of Some Methods for Evaluating Accident Probabilities and Consequences." IAEA-CN-39/4.

Crouch, E.A.C. and Wilson, R., 1982. "Risk/Benefit Analysis." Ballinger Publishing Company, Cambridge.

Kaplan, S. and Garrick, B. J., 1981. "On the Quantitative Definition of Risk." Risk Analysis, Vol. 1, No. 1, pp. 11-27.

Morgan, G., 1981. "Choosing and Managing Technology - Induced Risk." IEEE Spectrum, December, pp. 53-60.

Morgan, G., 1985. Personal Communication. July.

SENES Consultants Limited, 1984. "A Study to Develop and Demonstrate Techniques for the Probabilistic Assessment of the Long-Term Effects of Uranium Mill Tailings in Canada - Phase I." Research Report prepared for the National Uranium Tailings Program, CANMET, EMR, under Supply and Services Canada Contract No. 0SQ83-00236.

SENES Consultants Limited, 1985. "A Study to Develop and Demonstrate Techniques for the Probabilistic Assessment of the Long-Term Effects of Uranium Mill Tailings in Canada - Phase II." Research Report prepared for the National Uranium Tailings Program, CANMET, EMR, under Supply and Services Canada Contract No. 0SQ84-00207.

APPENDIX A

APPROACHES TO RISK ASSESSMENT FOR URANIUM MILL TAILINGS

PREPARED BY

R.V. OSBORNE AND P.J. BARRY
CHALK RIVER NUCLEAR LABORATORY

FOR

SENES CONSULTANTS LIMITED

ABSTRACT

All human endeavours entail some risk. It is generally agreed that the overall usefulness of an endeavour should outweigh its overall detrimental effects. Furthermore, it is necessary to provide a suitable level of protection for individuals and to attempt to allocate resources for risk reduction in a fashion commensurate with the protection obtained. The paper argues that risk-based criteria provide a coherent base for protecting individuals. The use of ALARA and a multicriteria approach to optimization are discussed. Finally, several issues related to both individual and collective risk are discussed. These include consideration of low-probability events, time and uncertainty.

TABLE OF CONTENTS

		Page
1.0	OVERALL OBJECTIVES IN RISK ASSESSMENT	A-1
2.0	CRITICAL GROUPS AND INTRUDERS	A-7
3.0	CRITERIA FOR LIMITING THE RISK TO INDIVIDUALS	A-10
4.0	DETERMINING WHAT IS REASONABLY ACHIEVABLE	A-14
4.1	Issues Related to Time	A-15
4.2	Issues Related to Uncertainty	A-16
4.3	Issues Related to Very Low Individual Doses	A-17
4.4	Issues Related to Geographical Distribution of Doses	A-19
4.5	Other Issues	A-20
5.0	INTRODUCING EVENTS OF LOW PROBABILITY AND THE IDEA OF COLLECTIVE RISK	A-21
6.0	THE USE OF COLLECTIVE DOSE IN A MULTICRITERIA APPROACH TO OPTIMIZING	A-22
	REFERENCES	

1.0 OVERALL OBJECTIVES IN RISK ASSESSMENT

The production, handling and management of wastes in any industrial or domestic endeavour are as much a part of the operation as the production of a usable product or service. The usefulness of any such endeavour may lie in the product, in the service, in the jobs created, or in some other feature; economic profit may accrue to the operators, to the workers, or to the nation. Similarly, detrimental effects may result from the endeavour. Such effects might have direct economic consequences - the need to construct wider roads for example. The effects may be losses of amenities - disruption of the landscape for example -and there may be effects on the health of workers or the general public. For any endeavour to be introduced and allowed to continue the overall usefulness of it should outweigh the overall detrimental effects from it.

Within this overall constraint on an endeavour there are constraints on what is tolerated by society. Even though enormous benefits to the nation as a whole may accrue from a particular product, we do not permit detrimental impacts on the health of a few individuals to rise in proportion. We see this reflected in the imposition of limits on the concentration of toxic materials in water and in the annual dose from radiation. That is not to say that the possibilities of detrimental effects on health are not tolerated. They are, but only to the extent that the effort made to avoid them is commensurate with efforts elsewhere in society. There is, as Siddall (1981), for example, has pointed out, a wide range in such efforts when expressed on a common scale such as dollars per life saved. Nevertheless we can get some guidance from this range as to what might be a reasonable expenditure.

There are therefore two constraints we must recognize as connected with human health. One is that individuals must be protected to an accepted level of safety. The other is that expenditures and efforts to improve safety for all people can reasonably be expected to be similar to those throughout Canadian society. This latter is particularly appropriate when public funds are involved, directly or indirectly, in paying for safety.

Uranium tailings are a source of toxic chemicals and radionuclides. Some effects on health occur only when the concentration of toxic material in the body or the radiation absorbed in the body from a radionuclide is above a particular threshold.* Such effects can be avoided by ensuring that concentrations and radiation exposures remain below such thresholds. If a relation between concentration in the body (or radiation dose) and a concentration in water, or air, or food can be established, then limits on such concentrations achieve the same end.

Conformity with a concentration or radiation dose limit cannot usually be guaranteed, particularly when future impacts are being considered. With an operating plant, a limit can be met since control can be imposed on, for example, the amounts of contaminants released. For future impacts from sources such as tailings, it is sensible to limit the probabilities that such limits may be exceeded. What that probability should be has only been discussed at length for radiation exposures. For illustrative purposes in the present discussion, assume a value of 10^{-5} per year. If we link all impacts as "health effects", then the limit for toxic chemicals and (non-stochastic effects of) radiation doses could be a limit to the sum of the probabilities g_i of chemical or radiation exposures exceeding threshold values;

---

* For radiation, the term threshold (i.e. dose threshold) refers to non-stochastic effects. On the other hand it is assumed that any radiation dose, no matter how small, has a probability of causing a stochastic effect. In addition it should be noted that de minimis levels of dose, risk or concentration provide a practical alternative to true biological thresholds. (See also Section 4.3)

$$\sum_i g_i < 10^{-5}\ a^{-1}$$

In principle, the probabilities for chemical and radiation effects could be combined within the one limit. This is not advocated here partly because it would be a radical departure from the regulatory practices to date although it is a logical direction. However, an additional reason to keep radiation impacts and chemical impacts separate follows from the hypothesis that at least some health effects from radiation are without threshold (i.e. stochastic effects). The same may be true for some effects from chemicals, but we know much less about the quantitative relations between small chemical exposures and effects than we do for the effects from radiation. The effects of concern here (stochastic effects) are those for which the probability of a fatal disease (or genetic damage) occurring depends on the magnitude of the radiation dose. The common (and likely conservative) assumption made is that the probability of a stochastic effect occurring as a result of a radiation exposure is linearly proportional to the magnitude of the radiation energy absorbed. There is known to be a dependence on the type of radiation involved, on the tissue or organ involved and on the particular disease. These dependencies can be taken into account for protection purposes by definition of an "effective radiation dose equivalent"*.

The proportionality coefficient between stochastic health effects (i.e. of the non-threshold kind) and dose we take as r per sievert. If the dose received from some particular event is H sieverts, the probability of a health effect from that event is rH. Following the previous discussion, if we place a limit on the annual probability in the future of a health effect in an individual of 10^{-5}, then the limit on annual dose, H, when such non-threshold effects are of concern, could be expressed as

$$r \cdot g \cdot H < 10^{-5}$$

where g is the probability of the dose H being received, i.e., the probability of the event occurring.

This is the basis for limiting "risk" defined as the probability of a health effect. In summary, for a single event with probability g that results in dose H, we have

$$r \cdot g \cdot H < 10^{-5}$$

for non-threshold effects for which linear proportionality is assumed between dose and probability of an effect, and

$$g < 10^{-5}$$

---

* This is detailed in numerous reports (see, for example ICRP 26,1977). It is sufficient to note that "dose" is used here to indicate this defined quantity when these non-threshold effects are considered. When threshold effects are considered a slightly different quantity, "dose equivalent" should be inferred. The unit of all these quantities is the same - sievert (or joule per kilogram).

if the dose is greater than the value for the onset of threshold (i.e. non stochastic) effects. This approach to limiting risk to individuals provides for coherence between chemical and radiation-related concerns, provided that a coherent set of threshold values and probabilities can be defined.

An approach to setting criteria based on risk as defined here is discussed in section 3.0.

The second constraint, noted earlier, is that of ensuring that the safety with respect to all people is reasonable. When applied to the management of uranium tailings it leads to the obligation to select a way of managing the tailings in which the allocation of resources is commensurate with the protection obtained. Any additional protection would be considered not worth the extra cost; on the other hand the extra protection attained with the way chosen compared with any other less costly way is considered to be worth the extra cost. This is a very general principle that has become somewhat formalized in radiation protection as the optimization or ALARA principle, the latter being the initials from the statement that doses should be kept as low as reasonably achievable.

With chemical toxicants for which a threshold exists to any detrimental effect on health, it might be argued that any reduction of concentrations to which individuals might be exposed below threshold values is unwarranted. However some caveats to this should be noted. A threshold applies to an individual. Any particular source of a contaminant cannot necessarily be allowed to expose an individual up to that threshold value; there may be other sources of contaminants. This possibility needs to be taken into account in setting appropriate limits on releases of contaminants from sources. It may be prudent to ensure that individuals on average in a local, regional, or even broader area are not exposed to concentrations of a contaminant from a single source above some small fraction of the threshold, to leave "room" for other sources. Hence for such chemical toxicants, a reasonable level of protection may be when some average exposure or concentration over appropriate population groups is a small fraction of any threshold value.

A similar approach might be used for radiation and radionuclides. Assurance that average doses (or the average probability of a health effect in an individual) over a population are likely to be a small fraction of a limiting value may be appropriate. How much should reasonably be spent, to get to what fraction, averaged over what population, remains a matter of judgement.

Because of the assumed linear proportionality between radiation dose and probability of health effects such as cancer and genetic disorders, it has been possible to develop the idea of ALARA and optimization in a quantitative way. This development follows from the assumption that the expected number of health effects from radiation exposure in a large population is proportional to the sum of all the individual radiation doses. (This is discussed extensively elsewhere - see, for example, ICRP (1977) and Lindell (1985)). The sum, termed the collective dose (units of man-sievert), is therefore a measure of the total impact on health or "detriment to health" (presuming that doses are sufficiently low to exclude non-stochastic effects). Since we can judge, on the basis of current societal practice, the "worth" of reducing such detriment - i.e. how much is spent to save lives in the statistical sense, not the lives of specific identified individuals - then collective dose reduction is a yardstick by which we can judge the reasonableness of spending on protection. A value of "dollars per man-sievert" can be defined as a target for spending on protection. The incremental spending on protection (i.e. in going from one way of managing tailings to another) and the predicted incremental reduction in collective dose can be judged against that dollar per man-sievert yard stick.

Although simple in principle, this method (differential cost-benefit or incremental cost-effectiveness) of determining what is ALARA when long-lived radioactive nuclides are involved is contentious and inconclusive in practice. Because of the difficulties in this kind of analysis, the general question of establishing when doses are ALARA has become a very confused issue in discussions of waste management and disposal. In section 4.0, these issues are discussed in detail and a somewhat more general approach to ALARA is suggested. It should be noted that the concept of "collective risk" is equivalent to the number of health effects in a population and, as discussed later, the collective dose or some component of it, is the most useful quantity for ALARA considerations.

2.0 CRITICAL GROUPS AND INTRUDERS

A logical start in a risk analysis is to identify the relations between health effects that result from exposure to radiation and events that can occur at or in the uranium tailings, events that can occur in the environment, and human activities.

There are four kinds of events. There is the biological event necessary for a dose to result in a health effect. Next are the events that occur as a result of human actions - the decision to grow and eat locally grown vegetables, to build a house on a tailings area, etc. Then there are the normal environmental events such as the airborne transport of particles, deposition on vegetation, etc. - the events determined by the dynamics of environmental processes. Finally, there are the events in the environment that are improbable, such as earthquakes or major floods. For the discussion in this section it is only necessary to consider the events that occur as a result of human actions. It is here that a risk analysis presents a dilemma. How do we determine the individual or group of individuals that is the "target" of any exposure?

The probability that there will be any effect on health as a result of the existence of the tailings will depend on the magnitude of the radiation exposure that anyone might receive. The magnitude of the exposure will depend partly on how far away from the tailings the exposure occurs. It is certain that some individuals will be exposed as a result of the existence of the tailings but they may be tens of kilometres away and the doses may be very small. It is less certain - and may be very improbable - that anyone will be exposed for, say, a 50 year period right at the tailings although doses may be highest there. The highest probability of a health effect in an individual may arise as a result of exposure at one or other of these extremes or somewhere in between. It is to this probability that the individual risk limit might be applied.

In analyses where dose to an individual is the impact that is to be limited - such as in determining the releases permitted from operating nuclear power stations, say - then "target" groups of individuals are defined whose existence, at least hypothetically, is not inconsistent with current local lifestyles and the institutional controls (such as fences) associated with the operating plant. For particular routes of release of particular radionuclides, the target group for which the radiation doses are highest is determined by calculation using pathways models as described elsewhere in this project (see Appendix C). The probability of this group existing, is for protection purposes, taken as unity. Such a group is termed the critical group for the given radionuclide, released by that route. The probability of any other group being more highly exposed is, by definition, zero. The concept of the critical group is an important one in radiation protection. That a group is involved is important. The objective is not to select or define an individual with extreme characteristics but to consider a relatively homogenous group whose characteristics may reasonably be expected to be shared by several tens of individuals.

With tailings, the protection afforded by institutional controls may perhaps not be taken as absolute in the long term. Yet the probability of exposures being incurred by a group of individuals as a result of, for instance, building houses on the tailings themselves, should be considered in an assessment of the probability of a health effect in an individual. The question is then how to include in an assessment the probability of a group of individuals being at a given location in order to be exposed. If one could determine how the probability of the existence of the target group varied with location with respect to a tailings area then a series of target groups might be considered. Such a determination seems infeasible. Therefore a pragmatic approach is to use the concept of a hypothetical critical group located in a manner consistent with the initial institutional controls for which the probability of exposure is taken as unity. We have to ensure that the probability of health effects to members of the critical group is below some limit, by considering all of the possible combinations of all events leading to a health effect.

The individual who builds, lives and eats on or adjacent to the tailings may be considered separately. Such an individual may be called the **intruder** and we have to consider whether the continuing existence of an "intrusion hazard" represents an unacceptable threat to individuals. Ideally we could estimate quantitatively the probability of someone intruding in any given period - say 50 years. In practice the best we can do may be to decide that the probability of intrusion is greater or less than the probability that we seem to accept for intrusion into other artifacts of civilization that may result in similar consequences.

3.0 CRITERIA FOR LIMITING THE RISK TO INDIVIDUALS

We have defined risk as

$$R = r \cdot g \cdot H$$

where H is the dose received, g is the probability of receiving that dose, and r is the probability of a deleterious effect on health per unit dose. In other words, risk is the probability of a health effect.

In a similar way, we can quantify the risk from a probability density p(H) of doses as

$$R = r \int_{0}^{\infty} H \, p(H) dH$$

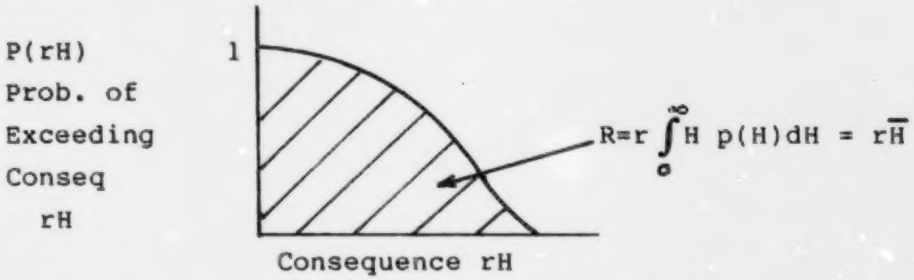
(Note that in this analysis, r is taken as constant. This is a reasonable simplification for radiation exposure in which a proportionality between probability of a health effect and radiation dose is usually assumed.)

The probability distribution p(H)dH may vary with time because of variations in some of the parameters in pathways models, or because of variations with time in the probabilities of occurrence of some initiating events (e.g., dam failures).

Since the integral above defines the mean dose, it follows that $R = r\overline{H}$ where $\overline{H}$ is the mean dose. **R is the statistical expectation of a health effect.**

We can compare R ($=r\overline{H}$) with a limiting value, R_{ref} say, to determine if the individual risk is acceptable.

The risk may also be represented by the downward cumulative probability distribution, or "tail distribution" since the risk as defined here is given by the area under the tail distribution.

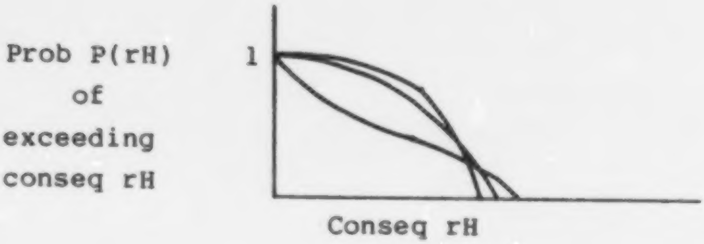


where the consequence rH is the probability of a health effect given a dose H and p(H)dH is the probability of receiving the dose H itself.

It follows that any tail distribution can represent a given risk (R_{ref}) provided that it has the correct area; i.e. any probability density function $P_{ref}(H)$ may be chosen for which

$$\int_0^\infty r\,H\,P_{ref}(H)\,dH = R_{ref}$$

Therefore any one of an infinity of criterion curves may be chosen for limiting risk as represented by a tail distribution.



If the tail distribution as estimated in a particular assessment lies within the area bounded by the reference distribution then the expectation or the risk is less than the reference value. If the distributions cross, then the expectation of risk may or may not be less than the reference value.

In other words, although a requirement that:

$$\int_H^\infty r\ H\ p(H)dH < \int_H^\infty r\ H\ P_{ref}(H)dH$$

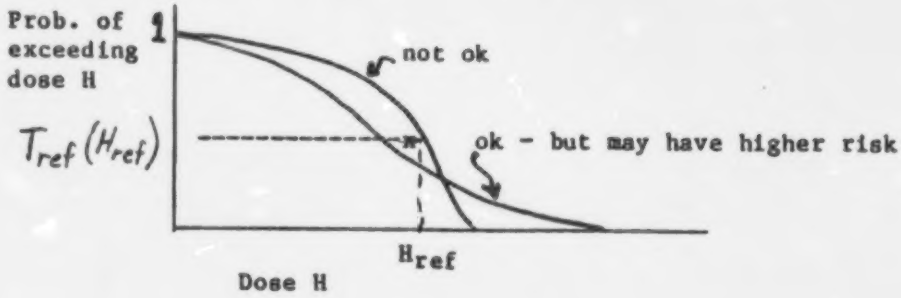
at all values of H is a sufficient condition for

$$R < R_{ref},$$

it is not a necessary one.

Hence the use of the tail distribution as a "criterion curve" is more restrictive than simply using total risk. If the tail distribution taken as reference ($T_{ref}(H)$) is similar to the expected tail distribution T(H) [=1 - P(H)], then the use of this criterion curve is similar to the use of the total risk criterion.

Another proposal is to use one (or several) combinations of dose and cumulative probability as a means of limiting "risk". That is, the probability of exceeding a defined dose (H_{ref}) has to be below a given value ($T_{ref}(H_{ref})$). Such a single definition may or may not be more restrictive than a total risk limit as shown below



We have therefore at least four possible criteria.

1. The total risk as represented by the expectation or mean of the estimated probability distribution of dose, for comparison with a single reference or limiting value of risk.

2. The total risk as represented by the area under a downward cumulative probability distribution (tail) of dose, for comparison with a single value of risk.

3. The estimated tail distribution of dose for a point by point comparison with a reference tail distribution, chosen so that the expectation value of the distribution is equal to or less than the reference value of risk.

4. The probability of exceeding a given single value of dose for comparison with a reference probability at that dose. (one difficulty with this approach is that many possible curves, with different consequences, may exist within the same area (probability) above the criteria level)

Some combination of these could also be used.

An important question is to ask what confidence we can have in estimates that we might make of probability density distributions or of measures of risk as defined here. If the distributions are estimated by a Monte Carlo sampling technique, then statistical techniques can be used to estimate, at a given confidence level, the limits to the actual distributions that result from the models and parameter distributions used.

The probability distributions of doses (or of probabilities of a health effect) so obtained then express the extent of our knowledge.

It may be of concern as to whether the shape of the estimated distribution (and the measures of risk) is sensitive to parameters for which we are confident that their probability distributions are accurately defined or whether it is more sensitive to parameters for which the probability distributions reflect more subjective "best judgements" as to what values they might have. Uncertainty may arise because we have not much information about a particular pathway or event. In some instances, more research may improve our knowledge and lessen uncertainty. However if the distributions truly reflect our best judgement, then from a strictly statistical point of view we need not distinguish between the different reasons. Nevertheless, from the point of view of improving the assessment, it is clearly worthwhile knowing whether the shape of the distribution could be altered by more information such as might be obtained by further research.

4.0 DETERMINING WHAT IS REASONABLY ACHIEVABLE

If we estimate, using available environmental models, the collective dose from a particular uranium tailings facility we may observe one or more of the following characteristics:

1. A substantial part of the dose is received by individuals at a very long time in the future (i.e. thousands, millions of years hence).

2. There are very large error bars on the estimate of collective dose.

3. A substantial part of the collective dose is received at very low individual dose rates (i.e. less than a few uSv.a^{-1}).

4. A substantial part of the collective dose is received by people outside the country in which the facility is sited.

Irrespective of the method used to optimize protection (i.e. ensure that doses are ALARA), it is clear that if collective dose or related concepts are to be used, value judgements are entailed. It is therefore useful to examine the issues that have arisen in applications to date where attempts have been made to optimize.

These issues are as follows.

4.1 Issues Related to Time

One argument is that the detriment to health that may occur in the far future should be valued less than detriment in the near future. This different valuation is irrespective of the certainty with which we can estimate collective dose commitments. Some form of discounting has been suggested, e.g. an exponential decrease in value with time. Economic arguments have been presented to support this, although they are not very convincing. (For a discussion see NEA (1984)). Alternatively, more pragmatic reasons have been presented to support the simple truncation of the time over which collective dose needs to be considered. One reason is simply that it is unreasonable to expect to have responsibility for civilizations many thousands of years in the future. For surface facilities, there is also the argument that the need for repairs to containment after, say, a few hundred years, could far more easily and cheaply be met at that time than by trying to ensure now that containment could remain effective for many years.

4.2 Issues Related to Uncertainty

In many instances, these issues are related to time as well. With long-lived radioactive waste, engineered controls over the containment of the waste cannot be guaranteed over times comparable to the half-lives of some of the radionuclides. There will therefore be an increasing uncertainty in the predicted release rates from a waste facility with increasing time. Distribution of the released waste over very long times results in a global distribution that cannot be predicted very accurately for several reasons. We may not have adequate models or appropriate parameters for the long-term processes involved, and there may be changes in the environment - climatic changes for example - or in population size, distribution, and habits. In many instances, estimating what the uncertainties are (i.e. the "error bars" on the estimate of collective dose) is impossible.

As a consequence of such uncertainties, it may be that no significant difference can be predicted in the estimates of collective doses for many options for managing a particular kind of waste. What this means, simply, is that the preferred option may be chosen on some other basis. Suppose for example, only a cost-benefit analysis were to be used as the "decision-aiding" tool in determining which of several disposal facilities would be the optimum. Because of modelling uncertainties, the benefits in terms of reductions in collective doses from increased expenditures are not apparent. Then the optimum would be the one with least engineering cost. (As will be discussed later, other radiological factors are likely to be considered.)

It has been suggested in the context of optimizing, that estimates of collective dose commitment could be made only for such times that the uncertainties in the collective dose rate are relatively small. In other words, comparison between options could be made using those portions of the collective dose that can be estimated with reasonable certainty. There is a hidden judgement in this, not usually acknowledged, that beyond those times when the uncertainties in collective dose rate are large, any detriment to health can be ignored. Without this judgement, there is no logical reason to apply the uncertainty in the collective dose commitment to only part of the quantity. A simple analogy is to think of comparing the total lengths of two posts that are protruding from the ground. The difference in exposed lengths is no indication of the difference in total lengths.

In some cases, it may be reasonable to assume that the collective dose rates from given radionuclides(s) in the environment are the same beyond some future time, even though they are uncertain. For example, if a long-lived radionuclide is retained in a repository for 100 years in one option and 10,000 years in another, the component of collective dose from the globally distributed nuclide after 10,000 years may be taken as common to both cases and therefore ignored in the comparison.

4.3 Issues Related to Very Low Individual Doses

There is considerable confusion in discussions of this issue with ideas on "de minimis", "trivial", or "negligible" doses.

If it is assumed that normal levels of radiation exposures increase the probability of deleterious effects on health, then it follows that successive relatively small increments in radiation exposures will increase the probability of such effects linearly. In a population, the increased expected number of deleterious effects will be proportional to the summation of all the small increments, i.e. to the collective dose. Hence, if we are considering populations and collective doses of sufficient sizes that we expect at least one deleterious effect to some individual's health, then it can be argued that the number of deleterious effects that will be expected depends only on the size of the collective dose.

Individual members of the public may choose to ignore exposures to radiation that present a very low probability of harm to themselves. Such low exposures may appropriately be termed "negligible" or "trivial". However, when a source of such exposures to many individuals is being considered it does not necessarily follow that the total impact of the source can also be ignored. Were it to be so, rapid dispersion of wastes would always be the preferred way of disposal. Not only would this tend to increase collective doses "in someone else's backyard", but there could be legitimate concern that if low individual doses associated with any particular source were completely ignored, then the doses from many such sources could add to non-trivial individual doses. Therefore to argue that small individual dose contributions to the collective dose can be ignored (merely because they are low) is not sufficient. Nevertheless, it can be strongly argued that we do allocate resources according to "health effect density" or in some way influenced by the probability of harm to individuals. Therefore, different distributions of individual doses perhaps should be taken into account in optimizing. It has to be done though with attention paid to whether there is the possibility of build up of doses from many sources and to concerns regarding geographical distribution of dose. These concerns are not readily included in a simple aggregative analysis (e.g. a cost-benefit analysis).

The same considerations counter the suggestion that assurance of very small (i.e negligible) individual doses from a particular practice is a sufficient criterion to regard the radiological impact from that practice as "de minimis" or exempt from normal control. Very small individual doses and a small collective dose from present and possible future sources may be sufficient conditions to define a practice as exempt. (An optimization analysis may show that any control is not warranted. Such a result, together with the individual dose criterion, may also be sufficient to exempt.)

4.4 Issues Related to Geographical Distribution of Doses

Undoubtedly, long-lived radionuclides from wastes will cross international boundaries, just as do chemical contaminants. In an attempt to ensure equitable treatment of trans-boundary radioactive pollution, the IAEA has suggested an "international value for dollars per man-sievert" or "international α value" as it is often termed to be used in cost-benefit analyses for optimizing. The intent is that this should be a minimum value for all countries and that if a country chooses to use a higher value for radiation doses within its boundary, then it would use no less a value for doses predicted to be incurred outside its boundary.

This may certainly be an equitable approach to strictly source-related analysis. However, it is difficult to separate "individual-related" considerations from the analysis; that is, not to consider the point of view of individuals in the receiving country. In a cost-benefit analysis, the extent of the control measures is determined from a consideration of the monetary valuation of the reductions in collective doses attained with the different controls. A consequence of this approach using collective dose reduction valued with, say, the international α, is that if a lightly-populated country is "downwind" of a polluting country, the "optimum" control of the source is likely to result in higher concentrations of the pollutant than would be the case for a heavily-populated country in a similar location. Greater spending on control measures and greater control would be warranted in the latter case. This is another instance where the logic of the strictly "source-related" analysis does not appear to be completely satisfactory.

4.5 Other Issues

Additional controversial points in the use of collective dose for optimizing arise in the relative weighting accorded public and worker doses, and in the choice of the value for . For the former, one suggestion is to use different values of for the two, reflecting the different individual limits. It is very much a subjective judgement however. For the latter, values suggested range from 100's of dollars per man-sievert to 100,000's. The value selected by the IAEA for the "international" value is $3000 per man-sievert (Ahmed and Daw, 1980).

Because cost-benefit analysis was cited by the ICRP as a way of optimizing protection, there have been many attempts to extend cost-benefit analysis to take into account some of the issues raised above. Attempts have been made to modify the monetary value assigned to the impact from radiation, in many cases by using some truncated collective dose quantity (in time or individual dose, as discussed above), others by including a "subjective" component related to the distribution of individual doses (see ICRP (1983) for a formal mathematical approach).

When so many value judgements are implicitly included in an analysis the significance and validity of any result is not readily apparent. For example, how the choice of optimum is affected by the truncation time, or the dose cut off, or even the value chosen for α are of interest to anyone trying to use the result. A sensitivity analysis is necessary to answer these questions. There still remain however, radiologically-related factors that are not readily incorporated into an aggregative analysis.

An explicit consideration of all of the factors that might affect the choice of an optimum with respect to radiation protection seems to be a preferable approach. An outline of a "multicriteria" analysis, involving collective dose and related radiological quantities is given in the final section.

5.0 INTRODUCING EVENTS OF LOW PROBABILITY AND THE IDEA OF COLLECTIVE RISK

As noted earlier in this paper, an individual "risk" can be defined as a product of a dose, a probability of a health effect occurring as a result of unit dose, and a probability that the dose will be received by an individual. This concept can be readily expressed as an integral to include a continuous probability distribution of doses such as might occur from modelling uncertainties. The expectation value represents the "risk" to the individual and this can be compared with an appropriate risk limit.

It follows that a "collective risk" could be defined in a manner analogous to the collective dose. Where the probability distribution represents modelling uncertainties, then "collective risk" could be used in much the same way as collective dose discussed earlier, with the same caveats applying. It does not appear to offer any particular advantages however. In either case, the comparison would be between mean values that have variances associated with them.

If events of very low probability are included however, the concept of expected collective dose is not very useful. In a situation where an event may result in a very large collective dose but its occurrence may be very improbable, the outcome is either zero - the most probable outcome - or a large collective dose. The expectation value of collective dose is small. As a consequence, the standard deviation of the collective dose is very large - it is inversely proportional to the square root of the probability of the event that resulted in the collective dose. A similar relation would hold for health effects ascribed to the collective dose. For example, if an event with probability of 10^{-4} of occurring can result in a collective dose of 10^6 man-sieverts to which we would ascribe $\approx 10^4$ health effects (using the ICRP risk factor), then the expectation would be 1 health effect with a standard deviation of 100. Comparisons on the basis of such quantities are not likely to be very useful. Separate consideration needs to be given to the probabilities of such disruptive events and the collective doses associated with them. It appears easier to do this in a multicriteria analysis than in an aggregative analysis.

6.0 THE USE OF COLLECTIVE DOSE IN A MULTICRITERIA APPROACH TO OPTIMIZING

In deciding which waste disposal option should be preferred, we might say that, all other things being equal, we would prefer the option that results in the most uniform distribution of collective dose over individuals. Alternatively, we may prefer the most uniform distribution over time, or a distribution with least dose in the near future. We may prefer an option with the least collective dose. A long list of such preferences can be developed encompassing all radiologically-related factors. We may feel very stongly about some, be fairly neutral to others. The multicriteria approach is merely a methodical, explicit listing of these preferences and their relative weights. It is not new - it is a well developed decision-aiding tool.

The method is:

(a) to select the options to be considered;
(b) to identify all of the radiologically-related factors that may indicate a preference for one option over another;
(c) to decide what the preferences are and the relative weights to be given to the preferences in comparisons between pairs of options;
(d) to compare the options on this basis.

Clearly judgements are needed for (a) and (b), just as in attempts to optimise through a cost-benefit analysis. The major advantage in this approach is that the analysis can be made apparent and debate can focus directly on the factors and weighting without the constraint of attempting to fit all factors into an aggregative analysis.

Such an analysis concerned with radiologically-related factors will only be part of an overall analysis that considers other impacts (social, technical, political, economic, resource commitment) for major whole management projects.

In some waste management analyses, it might be expected that radiological considerations such as collective doses might have an effect on some of the design details but in others only the major aspects may be affected. For example, radiological differences may be more significant between categories of options such as immediate release, storage and release, immediate disposal, storage and disposal, than between options that differ in technical detail, such an uranium mill tailings covered with 1 m of fill compared with 2 m of fill or between a nuclear fuel repository 1 km deep in a pluton or 1.2 km deep. It is in the broader analysis that considerations related to collective dose are more likely to be important in decisions.

Radiologically-related factors that could be considered in such a general approach to optimizing are listed below. More factors than those directly related to collective dose are given though it is not claimed that the list is complete.

Factors Directly Related to Individual Dose/Risk

- Maximum risk to the critical individual from facility
- Duration of maximum risk
- Time in future at which maximum occurs
- Dose and probability giving maximum risk
- Maximum average per caput dose in future that would be incurred if all waste of type considered were handled in this way
- Extent of reliance on institutional controls

Factors Related to Collective Dose

- Incremental cost-effectiveness between options using complete collective dose commitment
- Distribution of collective dose in time
- Frequency distribution of collective dose in individual dose
- Geographic distribution of collective dose

- Distribution of collective dose between workers and the public
- Certainty in collective dose estimates
- Probabilities associated with collective doses from low probability events

The preferences and the weights given to them are yet to be decided but such decisions are more readily made in this framework than in that of a cost-benefit analysis. Some are straightforward. For the maximum risk, the preference is for lower risk and, in this instance, there is an individual limit that must be met. This limit on individual risk and, possibly, a 'target' for global levels of individual dose are necessary conditions for an option to be accepted. The other factors only influence the choice from amongst the options that meet such limits.

The preference for time of maximum risk is not so clear cut - later rather than earlier may be preferred. It is clearly subjective. Similarly, for the other factors, the decision-maker has to indicate the preference explicitly. A distribution of the collective dose at very low individual doses rather than at higher individual doses may be preferred. This may be countered by a preference for avoiding transboundary contamination.

The explicit expressions of preference and weights provides for a "transparent" analysis and allows the conclusion of what are clearly subjective judgements in a sensible and, where appropriate, non-quantitative way.

References

Ahmed, I.V. and Daw, H.T., 1980. "Cost-Benefit Analysis and Radiation Protection." International Atomic Energy Agency Bulletin, Vol. 22, No. 516, pp. 13-22.

International Commission on Radiological Protection (ICRP), 1977. "Recommendations of the ICRP." ICRP Publication 26, Annals of the ICRP, Vol 1, No. 3.

International Commission on Radiological Protection (ICRP), 1983. "Cost-Benefit Analysis in the Optimization of Radiation Protection", ICRP Publication 37, Annals of the ICRP, Vol. 10, No. 2/3.

Lindell, B., 1985. "Applications of the Concept of Collective Dose in Radiation Protection". OECD/Nuclear Energy Agency Report.

Nuclear Energy Agency (NEA), 1984. "Long-term Radiation Protection Objectives for the Management of Radioactive Wastes." Report by an NEA Group of Experts.

Siddall, E., 1981. "Risk, Fear and Public Safety". Atomic Energy of Canada Limited, Report AECL-7404.

APPENDIX B

RISK ASSESSMENT OF CANADIAN URANIUM MILL TAILINGS

PREPARED BY

S. KAPLAN
KAPLAN ASSOCIATES INC.

AND

D. B. CHAMBERS, R. A. KNAPP AND L. M. LOWE
SENES CONSULTANTS LIMITED

ABSTRACT

This paper describes a methodology that can be used to assess risk from uranium mill tailings. The concept outlined is that risk can be defined quantitatively as sets of triplets which express the possible risk scenarios, the likelihoods of the scenarios, and the consequences of the scenarios. The approach is illustrated by application to a reference uranium mill tailings site.

TABLE OF CONTENTS

APPENDIX B

Page No.

1.0 INTRODUCTION B-1

2.0 QUANTITATIVE DEFINITION OF RISK B-1

3.0 THE ISSUE OF COMPLETENESS AND THE DEFINITION OF SCENARIOS B-2

4.0 FORMATS FOR EXPRESSING THE IDEA OF LIKELIHOOD B-4

5.0 EXPRESSING CONSEQUENCES B-7

6.0 APPLICATION TO CANADIAN URANIUM MILL TAILINGS B-8

- 6.1 The Base Scenario B-8
- 6.2 Events Capable of Altering the Basic Scenario B-10
- 6.3 Probability of Events B-11
- 6.4 Development of Scenarios B-11
- 6.5 Likelihood of the Scenarios B-13
- 6.6 Consequences of the Scenarios B-15
- 6.7 Damage Indices B-16
- 6.8 Development of Risk Curves B-19

REFERENCES

1.0 INTRODUCTION

The purpose of this paper is to describe and provide a numerical example of a methodology that might be used to assess the risk from uranium mill tailings. The methodology is based on the conceptual framework put forward by Kaplan and Garrick (1980). That is, it adopts the point of view that risk is defined quantitatively, and fundamentally, as a set of triplets expressing the possible risk scenarios, their likelihoods and their consequences. This point of view has been applied to the probabilistic risk assessment (PRA) of many nuclear power plants and in that application has evolved into a methodology of a very high order of sophistication. To apply this point of view to uranium tailings requires a few new twists, however.

The fact that, with a few twists, the same methodology used for nuclear plants also applies to tailings, to transportation of hazardous substances, to chemical plant risk and so on, serves to reinforce the idea that fundamentally risk "is" a set of triplets and that, viewed at this level of abstraction, the structure of a risk analysis is the same whatever the industry or whatever the type of risk being assessed. We begin the paper therefore by reviewing the set of triplets idea in general, we then apply it to the tailings example, and finally we provide a numerical example.

2.0 QUANTITATIVE DEFINITION OF RISK

If we look closely, we find that the idea of risk boils down to the following three questions:

1) What can happen? (i.e. what can go wrong?)
2) How likely is that to happen?
3) If it does happen, what are the consequences? (i.e. what are the damages?)

Thus, when we undertake to do a risk assessment of some venture or facility, we are basically seeking to answer these three questions. We may conveniently write the answers in the form of a triplet.

$$\langle s_i, l_i, x_i \rangle \qquad (1)$$

where s_i is a name or description of a "scenario" i.e. an answer to "what can happen?"; l_i is the likelihood of that scenario; and x_i is a "damage index" i.e. a measure of the consequences of the scenario. (If desired, x_i can actually be a vector of damage indices, giving different aspects or components of the consequences, e.g. damage to people, to property, to environment, wildlife, etc.)

If we now use brace brackets, $\{\ \}$, to denote "set of" and R to denote "risk", then we may write

$$R = \{\langle s_i, l_i, x_i \rangle\} \qquad (2)$$

That is, for analytic purposes, the risk is the set of triplets in equation (2) in the sense that this set answers our questions. It tells us everything we wanted to know about risk but were perhaps unsure how to ask. It does this of course if and only if the set is "complete", that is contains all possible scenarios. So let us discuss this issue briefly.

3.0 THE ISSUE OF COMPLETENESS AND THE DEFINITION OF SCENARIOS

Certain critics of quantitative risk analysis have argued that any list of scenarios, as in equation (2), developed in a risk study is necessarily finite whereas the actual list is infinite.

They use this argument to minimize and invalidate the value of any risk study, no matter how detailed and thorough, saying that they are not concerned with the scenarios on the list, but with those not on the list.

This argument has some merits along with demerits, so let us see how we can interpret and understand our definition, equation (2), to respond to this argument.

Let us observe first that when we define a "scenario" with some finite set of words, we are actually defining a whole category of scenarios. Thus, for example, suppose we define scenario #2 (S_2) as:

$$S_2 = \text{"the pipe breaks"} \qquad (3)$$

The pipe can break in many different ways, in many different places, at different times and under different circumstances. Thus the definition given by equation (3) actually encompasses this whole category of scenarios.

If we wished to increase the level of detail in our risk model, we could define smaller categories, e.g. "longitudinal pipe break", "guillotine break", etc. Each of these statements defines a smaller category but it is still a category. This is true however elaborately we define the scenario.

Observing, therefore, that all our scenarios are actually scenario categories, we can choose our words carefully when defining the s_i so as to make the set of categories complete.

Consider, for example, the uncontrolled (or at least unsatisfactorily controlled) release of waterborne radionuclides from a tailings impoundment. The list could have only one scenario:

$$S_1 = \text{"unacceptable release occurs"} \qquad (4)$$

However, while the list is logically complete it is not of much use. In order to analyse the "unacceptable release", we define smaller categories:

S_1 = "operator or equipment failure in treatment system leading to unacceptable release" (5)

S_2 = "failure of tailings impoundment leading to unacceptable release" (6)

These two scenarios also constitute a logically complete list. However, both S_1 and S_2 can be decomposed into smaller categories; for example, "operator or equipment failure" can be expected to include failure due to mechanical malfunction (of any type leading to unacceptable release), failure due to loss of electrical power and operator failure (of any type leading to unacceptable release). Completeness can be maintained at each level of refinement.

4.0 FORMATS FOR EXPRESSING THE IDEA OF LIKELIHOOD

The idea of likelihood can be expressed in several different ways, appropriate to different situations. For a first example, suppose the scenario, s_i, in question is the failure of the brakes in a certain category of large truck. We shall consider a partial failure to be a failure. Thus, each time the brakes are asked for (demanded), they either "work" or "fail".

Since there are many thousands of such demands each year, and a substantial number of failures, it is convenient to think about likelihood in terms of the "frequency", f_i, of brake failure, i.e. in terms of the number of failures per demand.

Similarly, with a piece of equipment that operates continuously, say a pump, we would express likelihood as a frequency measured in failures per unit time.

Thus, when we have a repetitive situation, the idea of likelihood is expressed as a frequency.

$$l_i \rightarrow f_i, \qquad \text{(failures per demand or failures per unit time)} \qquad (7)$$

Now, for a non-repetitive example, suppose we are contemplating a manned flight to Mars. This being a "one shot" situation, no frequency is involved. Here the appropriate expression of "likelihood" is "confidence". We ask "How confident are we that the crew will return safely?" The appropriate scale for measuring confidence is the probability scale. This is the so called subjective interpretation of probability as a quantitative measure of our degree of confidence, as dictated, not by our faith or our wishes, but by all the evidence, information and relevant experience available.

Thus, in this non-repetitive situation, the idea of likelihood is expressed as probability.

$$l_i \rightarrow p_i \qquad (8)$$

Returning now, for the next example to the case of brake failure, we may find ourselves in the following situation. Although the failure frequency is a well defined number, since there are many failures and very many demands, it may be that we do not know what the number is. It may be, for example, that the records have not been well kept. Thus we are in the position where we know f_i exists but we are uncertain about what its value is. We have only our own experience to go on, along with such data as we can locate, and possibly also the opinions of experts in the trucking industry. On this basis, we may express our state of knowledge in the form of a probability distribution, p_i, against f_i.

Thus, in this case, likelihood is expressed as a "probability of frequency" distribution

$$l_i \rightarrow p_i(f_i) \qquad (9)$$

Equation (9) together with equations (7) and (8) thus give us three different formats for expressing the idea of likelihood.

We note finally that the third format can also be applied to non-repetitive cases, like the Mars mission, if we are willing to imagine a thought experiment in which we launch millions of identical missions and ask in what fraction of these launches the mission fails. This thought experiment may seem a bit artificial and unnecessarily elaborate, and it is. On the other hand, it is important to note that we do not lose any information by it since from format (9) we can always obtain format (8) through the relationship:

$$p_i = \int_0^\infty f_i \; p_i(f_i) \; df_i \qquad (10)$$

Note in equation (10) that f_i plays the role of the conditional probability:

$$f_i = p\ (\text{failure} \mid f_i)$$

that is, if the true frequency of failure is f_i, then the probability of failure on the next demand is equal to f_i.

Thus, the probability of frequency format, equation (9), while it may not gain anything for us, at least does not lose anything.

On the other hand, it may gain a good deal for us. For example, while there may be only one Mars mission and only one Mars space vehicle, the individual components of the vehicle may have quite a bit of statistical history. For example, we may have much data on the failure rate of the control thrusters. Therefore, it may be convenient to express our knowledge of the reliability of individual components, using the probability of frequency format, and then combine these individual probability curves into a final curve giving the probability against frequency of failure for the mission as a whole. The general approach has been used in analysis of nuclear generating station as reported in Pickard, Lowe and Garrick (1981, 1982, 1983).

5.0 EXPRESSING CONSEQUENCES

In our basic definition of risk, equations (1) and (2), we have referred to x_i as a "damage index" which measures the consequences of the ith scenario. Actually, in most cases of risk analysis, we find that there are different types of damage that can occur. There are damages to people, to property, to environment, wildlife, reputation, etc. Each of these needs to be measured by its own damage index. We can therefore, think of the x_i in equations (1) and (2) as being actually a vector of damage indices, with each component measuring a different type of damage. Sometimes it is appropriate also to have the x_i be functions of time. This is the case as we shall see in the case of a tailings pile where $x_i(t)$ could represent for example the entire time history of leakage of hazardous materials from the pile.

6.0 APPLICATION TO CANADIAN URANIUM MILL TAILINGS

After the uranium has been removed, the processed ore from a uranium mine is deposited on the ground in what is known as a tailings pile. In addition to the residual uranium, the tailings contain various chemical constituents and several radioisotopes, notably radium-226. We wish to assess the risk posed by this pile to the surrounding environment and population. Therefore, in accord with our definition of risk in section 2.0, our first step must be to identify the possible scenarios. (The mathematical description of the "events" discussed in Sections 6.1, 6.2 and 6.3 is provided in Appendix C of this report.)

6.1 The Base Scenario

When we ask "what can happen?" to the pile, the first scenario we can envision is that after mining operations cease, nothing unusual happens. The reference tailings site simply sits there and experiences the gradual forces of rains, wind erosion, drainage, leaching, growth of vegetative cover, etc. This is called the base scenario, alternatively referred to as the "null" event.

To examine the performance of the pile under this scenario, a reference tailings site was defined and described in mathematical terms (see Appendix C of this report) as was a reference receptor. For the purpose of this discussion, which is to illustrate the methodology, a reduced set of exposure pathways is considered, as shown below:

RADON EXHALATION →	AIR DISPERSION		→ INHALATION
WIND EROSION OF TAILINGS →	AIR DISPERSION →	DEPOSITION ON VEGETABLES AND	→ INGESTION
		TRANSFER TO MEAT	→ INGESTION
			→ INHALATION
SEEPAGE → RIVER →	LAKE →	DRINKING WATER	→ INGESTION
		AND TRANSFER TO FISH	→ INGESTION

This reduced set makes the example more tractable. However, our experience suggests that even this restricted set of pathways illustrates all the salient features of pathways modelling and indeed are likely to account for the majority of the dose to the reference receptor.

For the present study, three human receptors were modelled to illustrate a range of possible situations. The reference receptor is assumed to be an adult male who lives year round in a cabin on a lake some 2 km downstream of the reference tailings site. Approximately 50% of this individual's food supply is from local sources such as berries grown in the area or fish taken from the lake. All of his drinking water is assumed to be from the lake.

The second receptor, referred to as the "downstream" receptor, lives further away from the tailings site and has more moderate living habits (i.e. he consumes a smaller fraction of local foods) than does the reference receptor.

The third receptor is an individual (with some characteristics similar to the reference receptor) residing on the tailings area. He is referred to as the "intruder". As discussed by Osborne and

Barry in a companion paper (see Appendix A of this report), this individual may require separate consideration. This aspect is also discussed later in this paper.

6.2 Events Capable of Altering the Basic Scenario

Various events of nature can be envisioned which might alter the dose delivered to humans (and other consequences) as calculated in the base scenario. For the the present example, we shall consider three such events as follows:

(i) Forest Fire

The effect of a forest fire is assumed to be a temporary reduction of vegetative cover with an attendant increase in windborne particulate and water erosion. For the present analysis, this event is modelled as a reduction in vegetative cover from 90% (null case) to 50%, with natural revegetation taking place over a period of 10 years.

(ii) Drought

An extended period of severe drought is assumed to result in a substantial reduction in vegetative cover (to 10% cover). Following the drought there is a gradual recovery of vegetative cover over a 20 year period. Increased wind and water erosion occurs during the period of reduced vegetative cover. During the drought the tailings moisture is reduced, leading to an enhanced radon exhalation.

(iii) Precipitation/Containment Failure (Flood)

The precipitation event considered here is actually the combination of two events, namely, a major precipitation event

(Event 1) leading to a dam failure (Event 2). A major solids release to the lake (assumed to be 10% of the impounded tailings mass) occurs in association with the precipitation event. This results in an immediate elevation of dissolved radium levels in the lake (decreasing with flow through) and long-term leaching of radium from the redistributed tailings solids which are assumed to deposit in the bottom of the downstream lake. This event also results in increased erosion from the remaining tailings mass.

6.3 Probability of Events

The annual probabilities of occurrence of the four basic events discussed above are given in Table 1. Also included in Table 1 are the probabilities of zero occurrences of the event and the probabilities of one or more occurrences of the event during the modelling period, which is taken as 1000 years. The annual probabilities of occurrence shown in Table 1 are subjective probabilities based on the current state of knowledge of SENES personnel. These values, while suitable for present (illustrative) purposes, would need to be reevaluated for an actual risk assessment.

Note that we have chosen to exclude intrusion , a human phenomenon, from Table 1. If one were to assume that intrusion could occur with an annual probability of 1×10^{-3}, then the probability that intrusion would not occur during the 1000 year modelling period would be 0.37 and the probability that intrusion would occur once or more during the same period would be 0.63.

6.4 Development of Scenarios

Scenarios are combinations of the natural events noted in Table 1, and possibly intrusion. The various events, of course, can

Table 1

Probability of Natural Events

Event	probability per year[1]	probability of non-occurrence in 1000 years[3]	probability of one or more occurrences in 1000 years[4]
Null[2]	9.98×10^{-1}	na	na
Forest Fire	2×10^{-3}	0.14	0.86
Drought	1×10^{-4}	0.90	0.10
Precipitation	5×10^{-5}	0.95	0.05

Notes

1. Subjective probability based on our current state of knowledge
2. Obtained by difference: Pr (Null) = 1 - [Pr(forest fire) + Pr (drought) + Pr (precipitation)]
3. (1 - annual probability of event)$_{1000}$
4. Obtained by difference: (1 - probability of non-occurrence)

occur in all combinations. To display all these possible combinations, we have prepared an event tree (Figure B.1 excluding intrusion and Figure B.2 including intrusion). In these event trees, we have put the most significant (in terms of consequence) events at the left and have used the probabilities given in Table 1 and in the text as the "split fraction" or "branching probabilities" at each branch point of the tree. Note that the way we have used these numbers implies that the bottom branches, labelled (n+) are to be interpreted as "n or more occurrences". Thus at the first branch point of Figure B.2 (assuming that intrusion occurs with an annual probability of 1 x 10^{-3}), the tree tells us that the probability of one or more intrusions during the 1000 year modelling period is 0.63. Similarly the probability of one or more droughts is 0.10. In the case of forest fires, we have shown branches representing 0, 1, 2, 3, and 4 or more occurrences. Multiple occurrences of forest fire were considered because of its greater probability of occurrence (and correspondingly higher return frequency).

Each path through the tree represents, therefore, a scenario for the 1000 year modelling period. For example, path 10 of either Figure 1 or 2 represents a scenario in which no intrusion occurs and no precipitation/dam breakage events occurs. However, there is a chance of one or more droughts and four or more forest fires during the life of the pile.

The set of paths in the event tree thus represents different scenario categories. Note that this set of scenarios is "complete" in the sense that if the three (or four) top events are a complete representation of the events that could happen in the life of the pile, then the 20 (40) paths in the event tree represent all possible combinations of the three (or four) basic events, including multiple occurrences.

FIGURE B·I

RISK EVENT TREE
(EXCLUDING INTRUSION)

EVENTS			Scenario		DAMAGE INDICES			
Precipitation	Drought	Forest Fires	Number	Probability	Max. Annual Dose (Sv/yr)	Max 50 yr Avg. Annual Dose (Sv/yr)	Cumulative (1000 yr) Population Dose (Sv)	Cumulative Radium Flux to Surface Water (Bq)
.951[a]	.905	.135	1	.116	$.989 \times 10^{-4}$	$.964 \times 10^{-4}$	9.70×10^{1}	2.4×10^{12}
		(.27)(1)[c]	2	.232	1.52×10^{-4}	$.996 \times 10^{-4}$	9.71×10^{1}	2.40×10^{12}
		(.27)(2)	3	.232	↓	↓	9.72×10^{1}	2.41×10^{12}
		(.18)(3)	4	.155	↓	↓	9.74×10^{1}	2.41×10^{12}
		(.145)(4+)[d]	5	.125	↓	↓	9.75×10^{1}	2.42×10^{12}
	(.095)(1+)	.135	6	.012	1.78×10^{-4}	1.03×10^{-4}	9.73×10^{1}	2.41×10^{12}
		(.27)(1)	7	.024	↓	↓	9.74×10^{1}	2.41×10^{12}
		(.27)(2)	8	.024	↓	↓	9.75×10^{1}	2.41×10^{12}
		(.18)(3)	9	.016	↓	↓	9.77×10^{1}	2.42×10^{12}
		(.145)(4+)	10	.013	↓	↓	9.78×10^{1}	2.42×10^{12}
(.049)[b](1+)	.905	.135	11	.006	8.54×10^{-4}	2.02×10^{-4}	1.02×10^{2}	2.43×10^{12}
		(.27)(1)	12	.012	↓	↓	1.02 x102	2.43×10^{12}
		(.27)(2)	13	.012	↓	↓	1.02×10^{2}	2.44×10^{12}
		(.18)(3)	14	.008	↓	↓	1.02×10^{2}	2.44×10^{12}
		(.145)(4+)	15	.006	↓	↓	1.02×10^{2}	2.44×10^{12}
	(.095)(1+)	.135	16	.0006	↓	↓	1.02×10^{2}	2.44×10^{12}
		(.27)(1)	17	.0013	↓	↓	1.02×10^{2}	2.44×10^{12}
		(.27)(2)	18	.0013	↓	↓	1.02×10^{2}	2.44×10^{12}
		(.18)(3)	19	.0008	↓	↓	1.03×10^{2}	2.45×10^{12}
		(.145)(4+)	20	.0007	↓	↓	1.03×10^{2}	2.23×10^{12}

Notes

a) p = probability of event not occurring in 1000 years

b) (p) = probability of event occurring in 1000 years

c) (n) = n events

d) (n+) = n or more events

FIGURE B-2

RISK EVENT TREE
(INCLUDING INTRUSION)

Intrusion	Precipitation	Drought	Forest Fires	Scenario Number	Probability	Max. Annual Dose (Sv/yr)	Max 50 yr Avg. Annual Dose (Sv/yr)	Cumulative (1000 yr) Population Dose (Sv)	Cumulative Radium Flux to Surface Water (Bq)
0.37[a]	.951	.905	.135	1	.043	$.989 \times 10^{-4}$	$.964 \times 10^{-4}$	9.70×10^{1}	2.4×10^{12}
			(.27)(1)[c]	2	.086	1.52×10^{-4}	$.996 \times 10^{-4}$	9.71×10^{1}	2.40×10^{12}
			(.27)(2)	3	.086			9.72×10^{1}	2.41×10^{12}
			(.18)(3)	4	.057			9.74×10^{1}	2.41×10^{12}
			(.145)(4+)[d]	5	.046			9.75×10^{1}	2.42×10^{12}
		(.095)(1+)	.135	6	.0045	1.78×10^{-4}	1.03×10^{-4}	9.73×10^{1}	2.41×10^{12}
			(.27)(1)	7	.0089			9.74×10^{1}	2.41×10^{12}
			(.27)(2)	8	.0089			9.75×10^{1}	2.41×10^{12}
			(.18)(3)	9	.0059			9.77×10^{1}	2.42×10^{12}
			(.145)(4+)	10	.0048			9.78×10^{1}	2.42×10^{12}
	(.049)(1+)	.905	.135	11	.0022	8.54×10^{-4}	2.02×10^{-4}	1.02×10^{2}	2.43×10^{12}
			(.27)(1)	12	.0044			1.02×10^{2}	2.43×10^{12}
			(.27)(2)	13	.0044			1.02×10^{2}	2.44×10^{12}
			(.18)(3)	14	.003			1.02×10^{2}	2.44×10^{12}
			(.145)(4+)	15	.0024			1.02×10^{2}	2.45×10^{12}
		(.095)(1+)	.135	16	.0002			1.02×10^{2}	2.44×10^{12}
			(.27)(1)	17	.0005			1.02×10^{2}	2.44×10^{12}
			(.27)(2)	18	.0005			1.02×10^{2}	2.44×10^{12}
			(.18)(3)	19	.0003			1.03×10^{2}	2.45×10^{12}
			(.145)(4+)	20	.00025			1.03×10^{2}	2.45×10^{12}
(.63)[b](1+)	.951	.905	.135	21	.073	3.24×10^{-1}	3.26×10^{-1}	1.79×10^{2}	2.4×10^{12}
			(.27)(1)	22	.146			1.79×10^{2}	2.40×10^{12}
			(.27)(2)	23	.146			1.79×10^{2}	2.41×10^{12}
			(.18)(3)	24	.098			1.79×10^{2}	2.41×10^{12}
			(.145)(4+)	25	.079			1.79×10^{2}	2.42×10^{12}
		(.095)(1+)	.135	26	.0077			1.79×10^{2}	2.41×10^{12}
			(.27)(1)	27	.0154			1.79×10^{2}	2.41×10^{12}
			(.27)(2)	28	.0154			1.79×10^{2}	2.41×10^{12}
			(.18)(3)	29	.01			1.79×10^{2}	2.42×10^{12}
			(.145)(4+)	30	.0082			1.79×10^{2}	2.42×10^{12}
	(.049)(1+)	(.905)	.135	31	.0038			1.83×10^{2}	2.43×10^{12}
			(.27)(1)	32	.0075			1.84×10^{2}	2.43×10^{12}
			(.27)(2)	33	.0075			1.84×10^{2}	2.44×10^{12}
			(.18)(3)	34	.005			1.84×10^{2}	2.44×10^{12}
			(.145)(4+)	35	.0041			1.84×10^{2}	2.45×10^{12}
		(.095)(1+)	.135	36	.0003			1.84×10^{2}	2.44×10^{12}
			(.27)(1)	37	.0008			1.84×10^{2}	2.44×10^{12}
			(.27)(2)	38	.0008			1.84×10^{2}	2.44×10^{12}
			(.18)(3)	39	.0005			1.84×10^{2}	2.45×10^{12}
			(.145)(4+)	40	.0004			1.84 x102	2.45×10^{12}

a - p = probability of event not occurring in 1000 years
b - (p) = probability of event occurring in 1000 years
c - (n) = n events
d - (n+) = n or more events

Adopting this point of view then, we can say that the 20 (40) scenarios in Figure B.1 (Figure B.2) are the complete set of scenarios, s_i, in our set of triplets.

6.5 Likelihood of the Scenarios

For this tailings pile model, it is appropriate to quantify the idea of likelihood by probability. Thus we simply want to express, at the present point in time and based on the evidence we have now, the probabilities (i.e. our levels of confidence or degrees of belief) that the 1000 year period will unfold according to each scenario category represented by the 20 (40) paths in Figure B.1 (Figure B.2).

To obtain these path probabilities, we simply multiply the branch probabilities along each path. For example, scenario 7 on Figure B.1, has probability 0.95 x 0.10 x 0.27 = 0.024. In this way, we obtain the scenario probabilities shown in Figures B.1 and B.2 and adopt these as the measures of likelihood, l_i, in our triplets.

It is worth noting that the probabilities of a much larger number of scenarios consisting of possible combinations of natural events were originally calculated using the multinominal distribution (a generalization of the binomial distribution). This approach neglects order of occurrence and assumes, in effect, that each scenario is a possible outcome from a thousand independent trials, one for each year of the modelling period. In this case, the probability that in 1000 trials there would be N_A forest fires, N_B droughts, N_C precipitation events and N_D null events is:

$$\left[\frac{1000!}{N_A!N_B!N_C!N_D!}\right] P_A^{N_A}\cdot P_B^{N_B}\cdot P_C^{N_C}\cdot P_D^{N_D} \qquad (16)$$

where the P_A ... P_D are the annual probabilities of occurrence of the natural events shown in Table 1 and N_A ... N_D are non-negative integers such that

$$N_A + N_B + N_C + N_D = 1000 \qquad (17)$$

The event tree shown in Figure B.2 explicitly includes the most probable scenarios, with the remaining low probability scenarios being included in the n^+ categories.

The present analysis does not explicitly account for simultaneous occurrence of two rare events (e.g. forest fires and drought in any particular year). It is clear, however, that such occurrences are rare. The chance that two events occur in the same year is smaller by a factor of 1/999 than is the chance that the two events will occur in any two years of the simulation period. Moreover, the effects of two events occurring in the same year (or within a few years of each other) would not be much different than the larger of the effects occurring from either event. For example, a precipitation event followed by a forest fire would lengthen the period required for vegetation cover to grow back but would not (at least for the models used in this study) lead to higher doses to the receptors.

Intrusion is distinctly different. It is not the result of a natural event; rather, it arises as the result of one or more individuals who build on or with tailings and could (but not necessarily would) arise from the failure of institutional controls over the long term. The possibility of human intrusion is independent of the occurrence (or non-occurrence) of the natural events and was thus not included in the calculations implicit in equations 16 and 17 and Table 1.

Figure B.2 illustrates the effect of including intrusion (or an event independent of natural events) in the event tree. An arbitrary, assignment of an annual probability of intrusion of 1×10^{-3} was assumed. Since the emphasis of this paper is on the methodology of combining risks from different scenarios, this arbitrariness is not a major drawback.

6.6 Consequences of the Scenarios

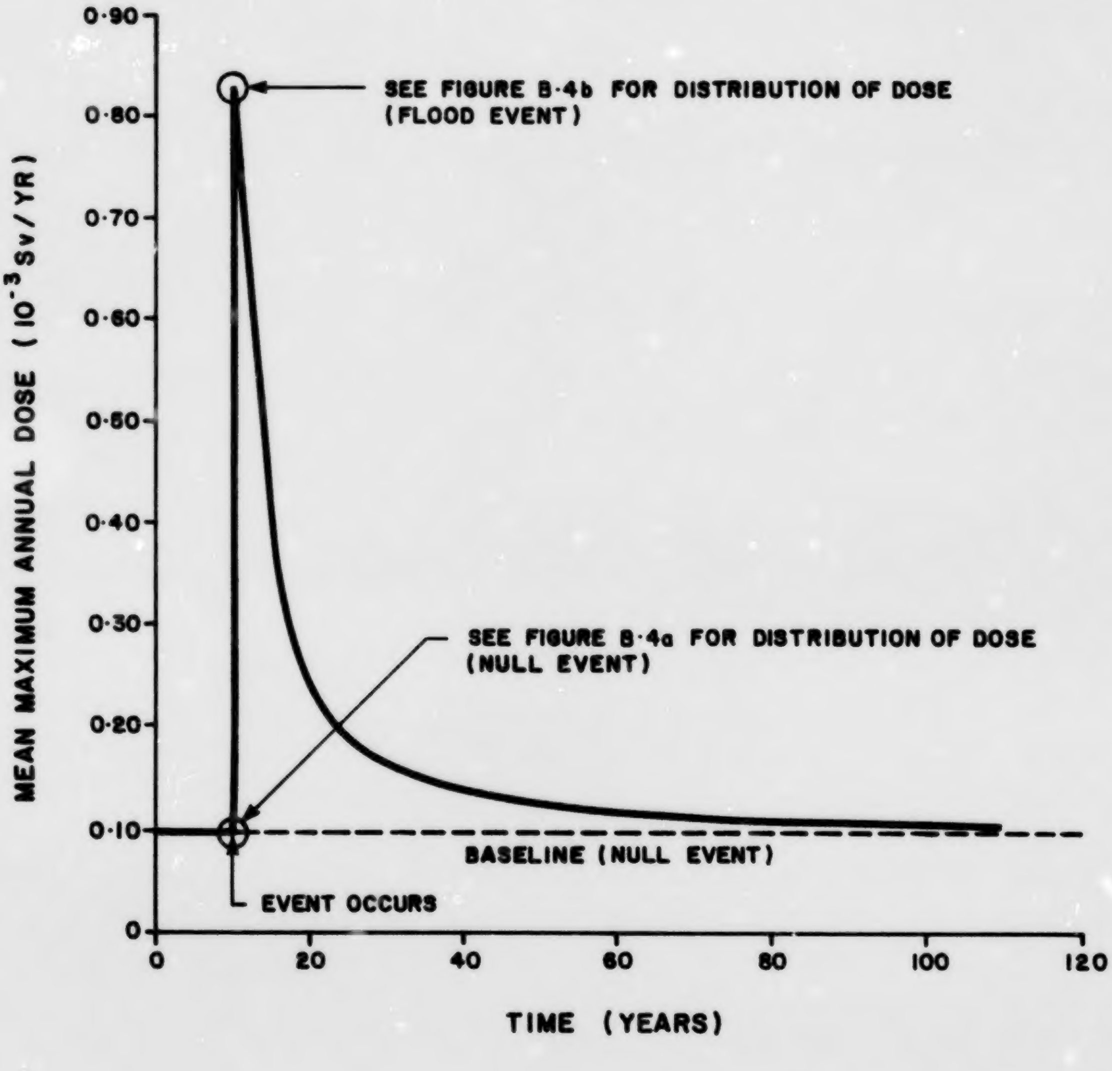
To assess the consequences of the scenarios, mathematical models tracing the movement of radioactivity to man along the three pathways shown earlier were used. These models were evaluated probabilistically to produce frequency distributions of calculated results. Such distributions can be summarized by a variety of descriptive statistics.

The basc tailings models used in this study were quasi-steady state models, with the distribution of the hazardous materials always at the levels which would be obtained in a true steady-state system. On the long time scale of interest to this study, routine fluctuations in wind and rainfall can be averaged out. There is a long term time dependence governed by movement, and the change in the physico/chemical form, of the hazardous materials within the pile itself. This long term time dependency, which is complex, is itself the subject of a separate study (SENES 1985) and is not discussed further here.

The time dependency of consequence due to major natural events such as floods or forest fires was accounted for explicitly in the mathematical simulations. This is illustrated in Figure B.3, which shows the time dependent behaviour of total annual dose to the reference receptor for a single flood event. The points plotted represent the arithmetic mean values, at each time, of 200 random trials. Following the event, the dose immediately rises rapidly and then returns to pre-event (baseline) levels in

FIGURE B·3

TIME VARYING BEHAVIOR: MAXIMUM ANNUAL DOSE TO REFERENCE RECEPTOR (FLOOD EVENT)



approximately 100 years. Figure B.4 shows the distribution of overall total dose to the reference receptor arising from the null event (the base case) and during the year immediately following a flood event. The mean dose in the year of the flood event is about 8.5 times greater than the mean dose during a baseline year. Both distributions of dose are positively skewed (more detailed descriptions of the models, parameters and results of these simulations are provided in Appendix C of this report.)

6.7 Damage Indices

From these results we can construct, for convenience, a series of consequence or damage indices. The damage indices are all determined from results presented in Tables C.3 to C.6.

Since the models described in Appendix C were evaluated probabilistically, the results presented there include an indication of the uncertainty in calculated values. It was decided, for ease of presentation, to include only the arithmetic mean values of all relevant results in this section. Hence, the consequences (damage indices) presented on Figures B.1 and B.2 do not indicate the uncertainties associated with the results. The information presented in Appendix C is sufficient to allow any interested reader to expand this analysis to incorporate the uncertainty in calculated values.

(1) Maximum Annual Dose (mSv/yr)

This is the maximum single year dose, over the 1000 year modelling period to any individual with the characteristics of the reference receptor (i.e. living on a lake 2 km from the tailings site). It is assumed to occur in the year immediately following any natural event. For both the null event and the tailings intruder, this dose is received every year of the

FIGURE B·4a

MAXIMUM ANNUAL DOSE TO REFERENCE RECEPTOR (NULL EVENT)

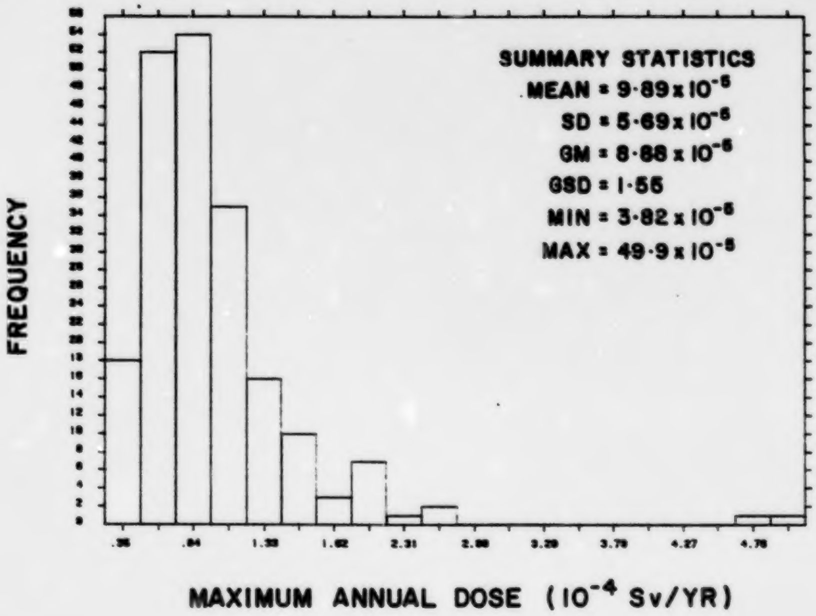
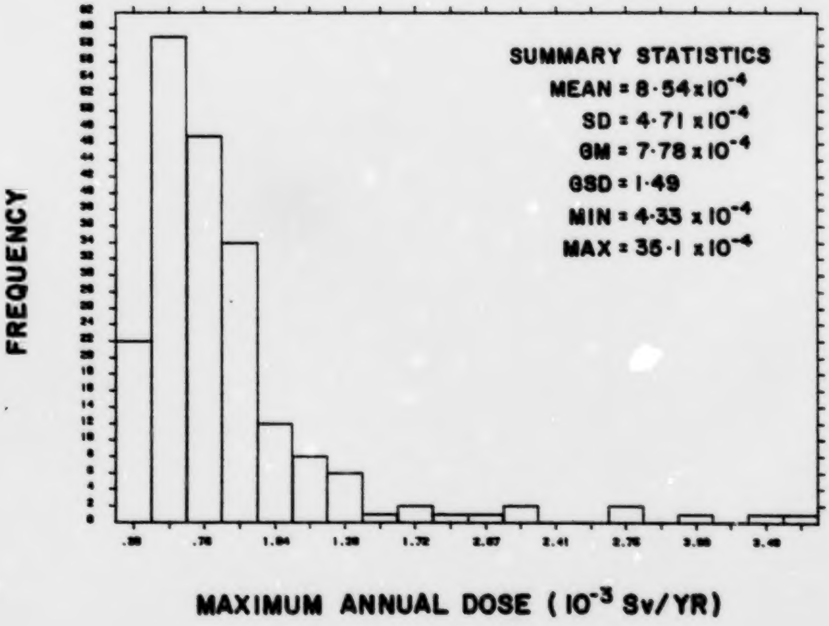


FIGURE B·4b

MAXIMUM ANNUAL DOSE TO REFERENCE RECEPTOR (FLOOD EVENT)



modelling period. For scenarios involving several events, it is equal to the greatest maximum annual dose of any event in the scenario.

(2) Maximum 50 year Average Annual Dose (mSv/yr)

This is the average annual dose over that 50 year period which gives the highest (50 year) dose in the modelling period. This index is thus intended to represent the maximum lifetime dose to a reference individual living in the vicinity of the pile. For scenarios involving several events it is equal to the greatest 50 year average annual dose of any event in the scenario.

(3) Population Dose (Sv/1000 years)

This is the cumulative total dose received by various receptors over the full 1000 years of simulation by a population consisting of:

i) the townsite group of 10,000 persons with the characteristics of the downstream receptor who (with replacement) are exposed for 1000 years.

ii) the intruder group, 5 persons living on the pile itself for 50 years.

Note that other groups could also be considered, if desired.

The cumulative population dose was calculated using the cumulative downstream receptor results of Table C.5 and the annual dose to the intruder (from Table C.3). For each scenario, appropriate combinations of the individual cumulative results were summed to produce a cumulative population dose.

(4) Contaminant Flux (Bq/1000 years)

The cumulative environmental loadings of radionuclides (or other tailings constituents) can also be estimated for the 1000 year simulation period. The flux of radium from the tailings to the surface water was used to illustrate this type of damage index.

The numerical values of these damage indices, for the various scenarios, are listed at the right in Figures B.1 and B.2. Recalling that each scenario, in fact, represents a whole class (or category) of scenarios, it follows that each consequence (damage index) noted on the figures represents a corresponding category of consequences. From these values, and the calculations supporting them, we may draw the following observations:

(1) The most significant event, in terms of human exposure, is the intrusion event. While this event does not significantly increase the release of materials from the pile, those humans who go to live on top of the pile will experience a much greater dose.

(2) The occurrence of one or more forest fires produce only very minor and very temporary increases of materials released from the pile.

(3) A major flood causing dam breakage results in almost a nine-fold increase in maximum individual dose and a two-fold increase in maximum lifetime dose.

(4) A prolonged drought causes only a slightly increased release, mainly via the water ingestion pathway.

(5) Non-routine events have little impact on the long term dose to the population as a whole, other than intruders.

6.8 Development of Risk Curves

With the assignment of damage index values we have completed our quantification of risk. That is, each path in Figures B.1 or B.2, each line, now represents a scenario s_i, with the l_i and x_i given in the last five columns. Thus, each line is a triplet $<s_i, l_i, x_i>$. The set of lines, the whole of Figures B.1 or B.2, is the set of triplets and therefore "is" the risk R from the tailings pile.

To express this risk we follow the procedure set out by Kaplan and Garrick (1980). If, for example, we wish to construct a risk curve using maximum annual dose to the reference receptor as our consequence, we refer to the maximum annual dose, and scenario probability columns in Figure B.1. From the figure, it is obvious that only four maximum annual doses were calculated (corresponding to each of the four events). To construct the risk curve, we must also determine the cumulative probability that each dose would occur, during the 1000 year modelling period. This is done by summing the scenario probabilities from bottom to top (i.e. from highest to lowest damage) which results in a downward cumulative probability curve. The cumulative probability of being in the highest damage category (maximum mean annual dose of 1.78×10^{-4} to 8.54×10^{-4} Sv/yr) is 0.0487. Similarily, the cumulative probability of a maximum annual dose as large as 1.78×10^{-4} Sv/yr is 0.089. In this way a table can be constructed as shown below:

Max. Annual Dose (Sv)	Cumulative Probability
8.54×10^{-4}	0.0487
1.78×10^{-4}	0.1377
1.52×10^{-4}	0.882
0.989×10^{-4}	1.0*

This table can be converted to a "risk curve", by plotting the damage index (in this case, maximum annual dose) on the horizontal axis, and the cumulative (greater than) probability on the vertical axis. This is shown in Figure B.5.

The step function risk curves, with (i) population dose including the intruder (ii) population dose excluding the intruder and (iii) radium flux to surface water as damage indices are presented in Figures B.6, B.7 and B.8, respectively. The risk curves show some expected trends. The radium flux curve, and the population dose curves (excluding intrusion) are dominated by the null event; that is, the various natural events have only a small probability of increasing dose or flux. The intruder scenarios, when considered in "population dose", have a significant effect on the shape of the risk curve.

These curves summarize a large amount of information and can be used, in particular, to provide an estimate of the probability of exceeding a given value of any damage index (for any scenario, i.e. any combination of events). For instance, the probability of a maximum annual dose to the reference receptor greater than 5 x 10^{-4} Sv/yr is (from Figure B.5) approximately 0.05

---

*probabilities on Figure 1 may not add to 1.0 because of rounding. However, the cumulative probability must sum to 1.0 by definition.

FIGURE B·5

RISK CONSEQUENCE CURVE
MAXIMUM ANNUAL DOSE TO REFERENCE RECEPTOR

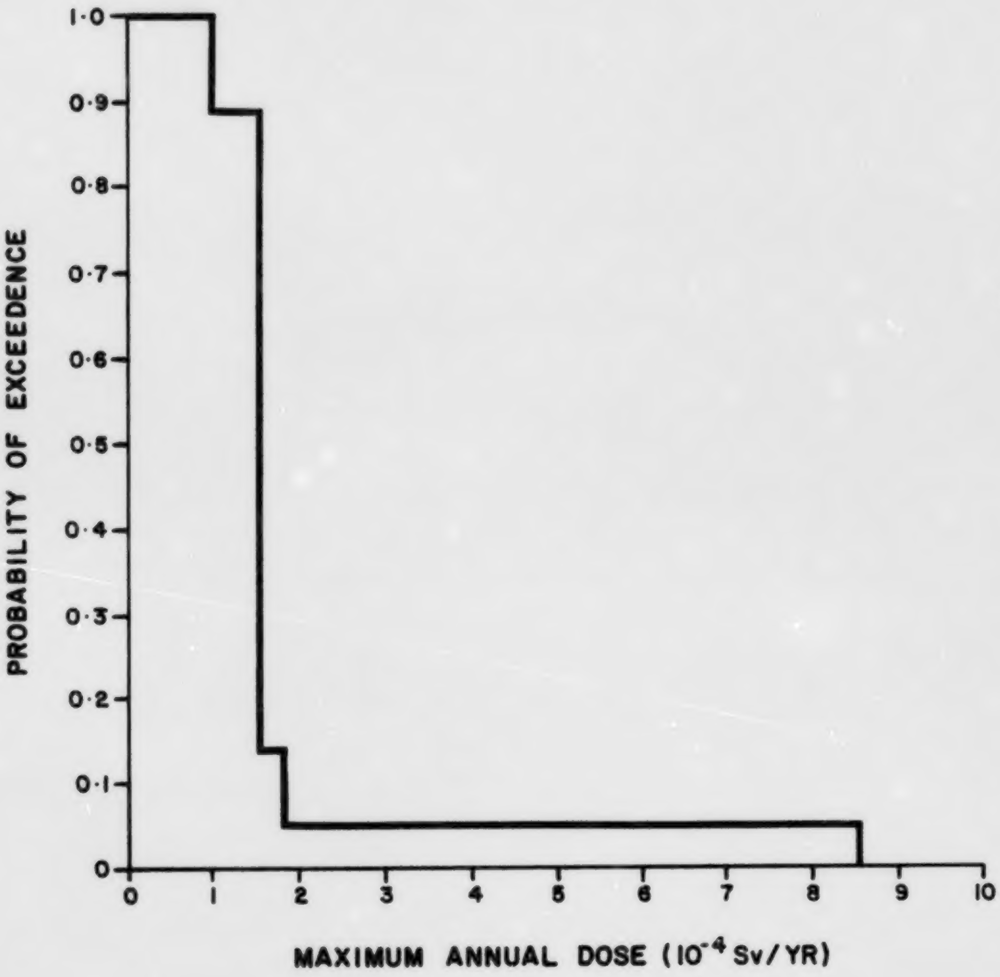


FIGURE B·6

RISK CONSEQUENCE CURVE
CUMULATIVE (1000 YR) POPULATION DOSE
(NO INTRUDER)

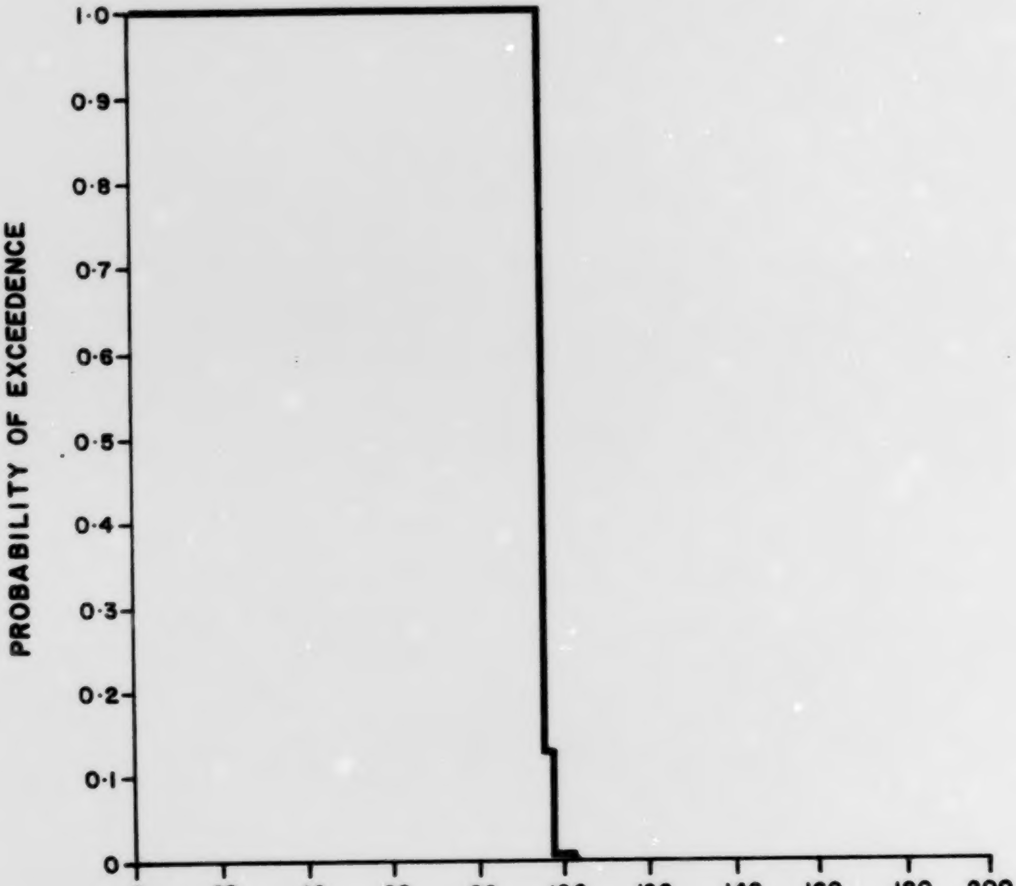


FIGURE B·7

RISK CONSEQUENCE CURVE
CUMULATIVE (1000 YR) POPULATION DOSE
(INCLUDING INTRUDER)

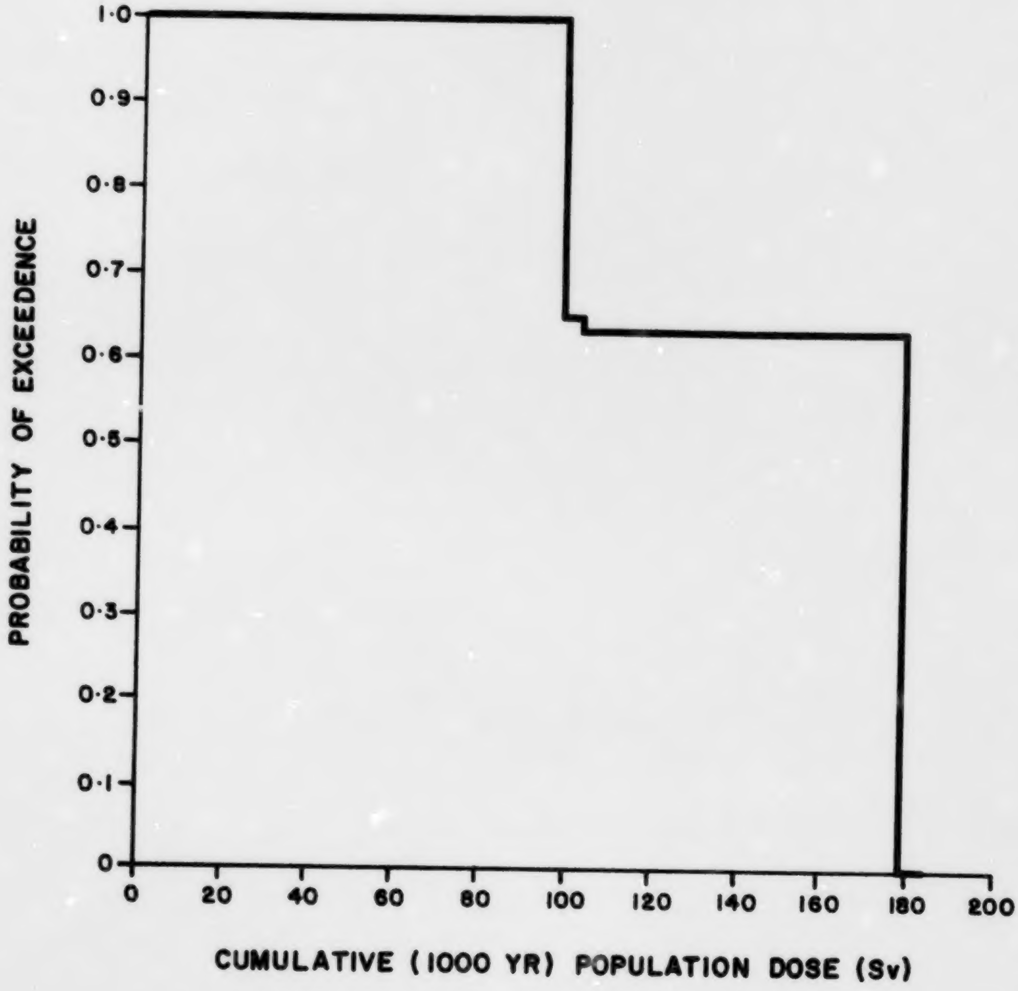
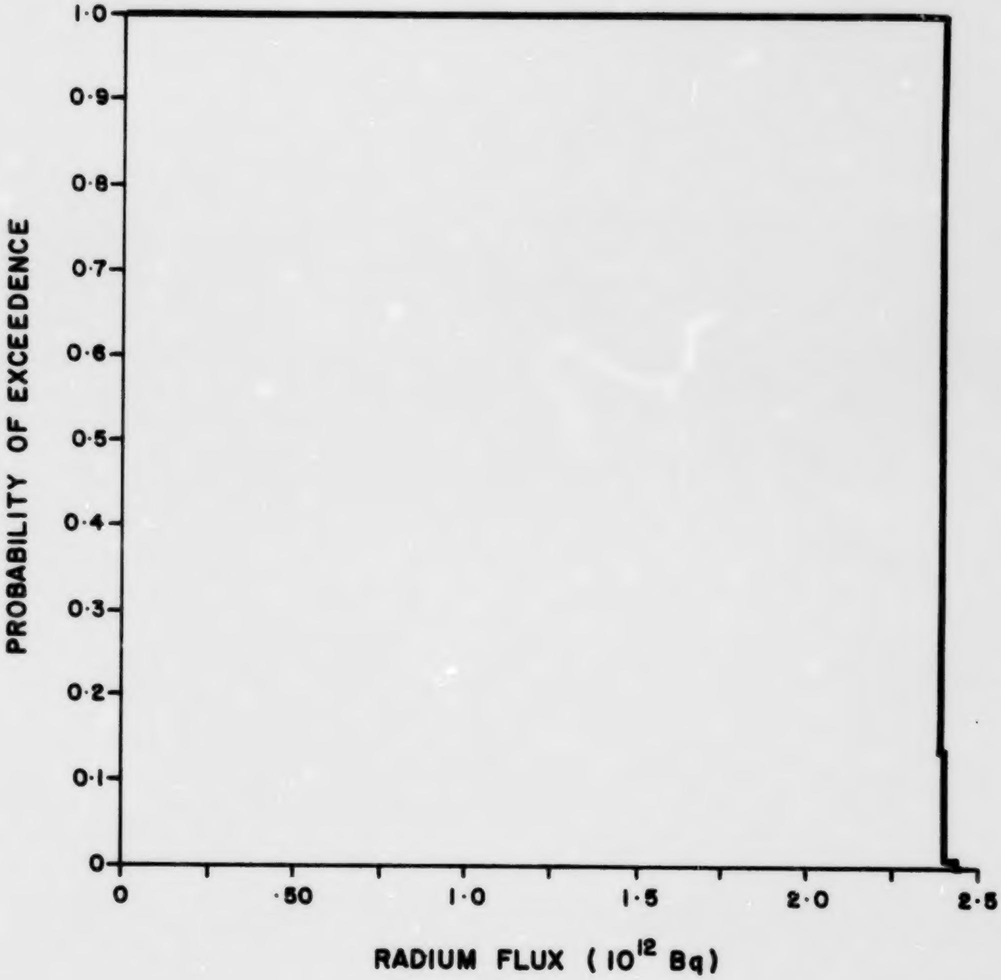


FIGURE B·8

RISK CONSEQUENCE CURVE CUMULATIVE (1000 YR) FLUX OF RADIUM TO SURFACE WATER



REFERENCES

Kaplan, S., and Garrick, B.T., 1981. "On the Quantitative Definition of Risk." Risk Analysis, Vol. 1, No. 1.

Pickard, Lowe and Garrick, Inc., Westinghouse Electric Corporation, Fauske and Associates Inc., 1981 (Sept.). "Zion Probabilistic Safety Study" prepared for Commonwealth Edison Company.

Pickard, Lowe and Garrick, Inc., Westinghouse Electric Corporation, Fauske and Associates Inc., 1982 (March). "Indian Point Probabilistic Safety Study." Prepared for Power Authority of the State of New York and Consolidated Edison Company, New York, Inc.

Pickard, Lowe and Garrick, Inc., 1983 (Dec.). "Seabrook Station Probabilistic Safety Analysis." Prepared for Public Service Company of New Hampshire and Yankee Atomic Electrical Co., PO60300.

SENES Consultants Limited, 1984. "A Study to Develop and Demonstrate Techniques for the Probabilistic Assessment of the Long-Term Effects of Uranium Mill Tailings in Canada - Phase I." Research Report prepared for the National Uranium Tailings Program, CANMET, EMR, under Supply and Services Canada Contract No. 0SQ83-00236.

SENES Consultants Limited, 1985. "A Study to Develop and Demonstrate Techniques for the Probabilistic Assessment of the Long-Term Effects of Uranium Mill Tailings in Canada - Phase II." Research Report prepared for the National Uranium Tailings Program, CANMET, EMR, under Supply and Services Canada Contract No. 0SQ83-00236.

APPENDIX C

DESCRIPTION OF ENVIRONMENTAL MODELS USED TO ILLUSTRATE APPROACH TO RISK QUANTIFICATION AND ASSESSMENT

PREPARED BY

M. L. MURRAY, D. B. CHAMBERS AND R. A. KNAPP

SENES CONSULTANTS LIMITED

ABSTRACT

In order to demonstrate the approaches to risk analysis, a simplified, though relatively realistic example was selected. This appendix describes the characteristics of the reference tailings site modelled and the pathways of environmental exposure considered. The mathematical models used to simulate the source, environmental transfer and dose conversion terms are presented and derived (at varying levels of detail). As well, several different receptors were modelled and various consequences to these receptors were calculated. All are described in this appendix. The parameters used as input to the models are also summarized and tabulated. Finally, the probabilistic results, for a variety of events, times and consequences are presented.

TABLE OF CONTENTS

APPENDIX C

Page No.

1.0 INTRODUCTION C-1

2.0 ATMOSPHERIC PATHWAYS: COMPONENT MODELS FOR RADIUM C-4

- 2.1 Source to Air C-4
- 2.2 Atmospheric Transport C-7
- 2.3 Atmosphere to Vegetation C-10
- 2.4 Vegetation to Animal Produce C-10
- 2.5 Vegetation to Dose C-11
- 2.6 Animal Produce to Dose C-12
- 2.7 Atmosphere to Inhalation Dose C-12

3.0 SURFACE WATER PATHWAYS: COMPONENT MODELS FOR RADIUM C-13

- 3.1 Source to Water C-13
- 3.2 Transfer to Surface Water C-26
- 3.3 Surface Water to Aquatic Animals C-29
- 3.4 Aquatic Animals to Dose C-30
- 3.5 Surface Water to Dose C-30

4.0 ATMOSPHERIC PATHWAYS: COMPONENT MODELS FOR RADON C-31

- 4.1 Radon Source Term C-31
- 4.2 Source to Atmosphere C-36
- 4.3 Atmosphere to Inhalation Dose C-36

Table of Contents-Appendix C (continued) Page No.

5.0 DETAILS OF RECEPTORS MODELLED C-37

5.1 Reference Receptor C-37
5.2 Downstream Receptor C-37
5.3 Tailings Intruder C-38

6.0 PARAMETER DESCRIPTIONS AND DISTRIBUTIONS C-41

7.0 CALCULATION METHODOLOGY C-42

8.0 RESULTS C-42

8.1 Maximum Annual Dose C-42
8.2 50 Year Average Annual Dose C-43
8.3 Cumulative Consequences C-45

REFERENCES

1.0 INTRODUCTION

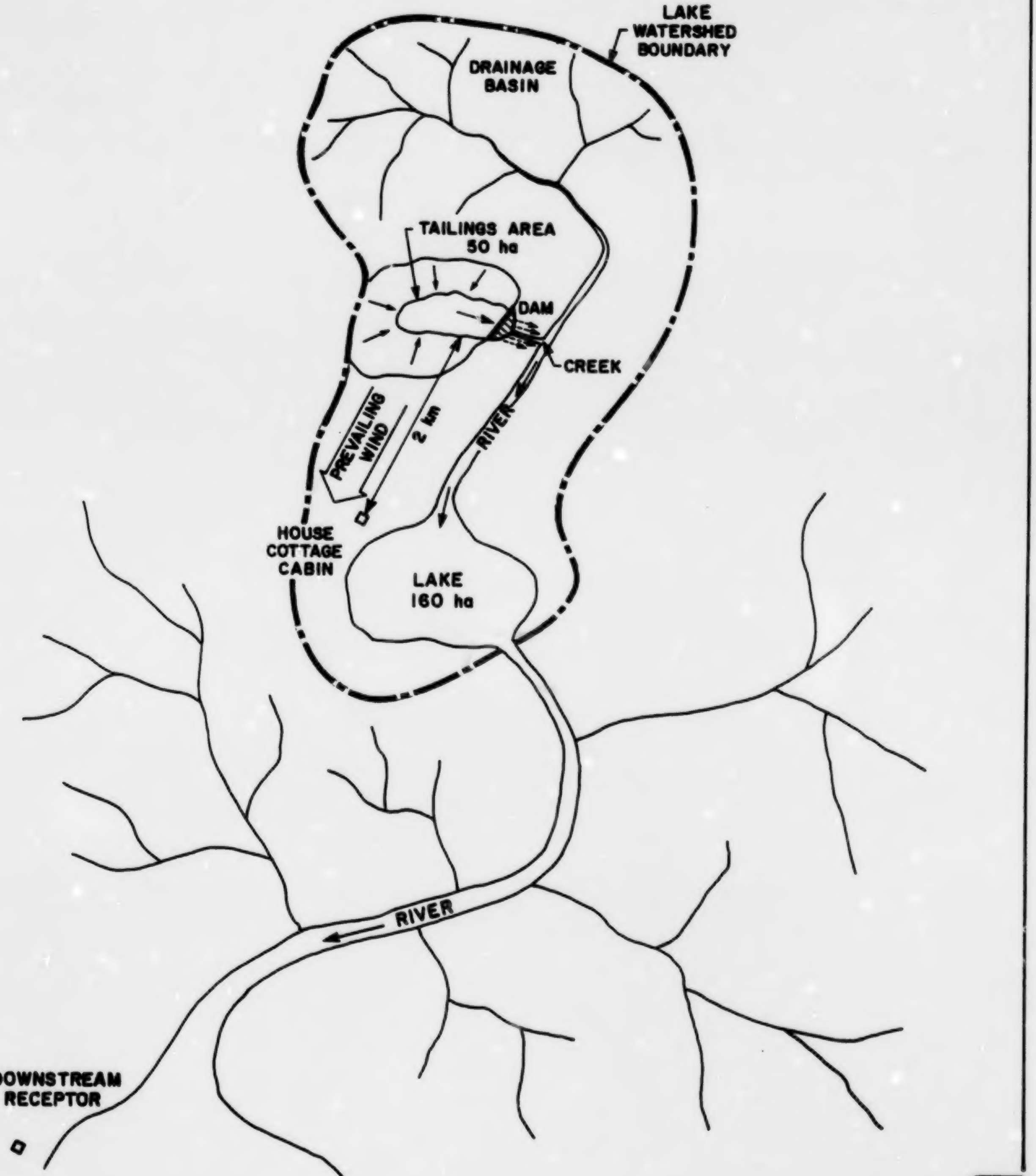
The mathematical models used in this report to illustrate the potential environmental effects arising from a uranium tailings area were adapted from those developed as part of an earlier NUTP project (SENES 1984). As discussed in the 1984 study, in order to simplify the analysis a hypothetical reference site with several simple features was chosen to reflect the major environmental pathways pertinent to tailings management on the Canadian Precambrian Shield. Further, the radionuclides considered were restricted to radon gas release from the tailings surface, radium dispersal with windblown particulates and dissolved radium transport in surface water and groundwater.

The basic characteristics of the hypothetical reference site are shown on Figure C-1. The tailings disposal site occupied a natural depression formed within the upper reach of a valley. The tailings were contained behind a conventional slightly pervious dam constructed across the low point. Surface and groundwater flows from the site were assumed to follow the valley feature with ultimate discharge to a major river which flows into a lake. The reference tailings site was defined to have a surface area of 50 ha and an average tailings depth of 10 m for a total volume of $5 \times 10^6 m^3$. The natural depression containing the tailings covered 150 ha; the total area of the drainage basin at the outflow of the lake equalled 2000 ha.

The reference tailings characteristics represent those resulting from the acid leaching of low-grade pyritic uranium ore containing 0.1 to 0.2% uranium with 95% recovery efficiency. All other radionuclides were stipulated to remain with the tailings. The tailings were considered to be neutralized in the mill by lime addition prior to discharge to the tailings areas. Specifically, the principal characteristics of the tailings were:

FIGURE C-1

SCHEMATIC ILLUSTRATION OF WATERSHED SETTING FOR THE REFERENCE TAILINGS SITE


LAKE WATERSHED BOUNDARY
DRAINAGE BASIN
TAILINGS AREA 50 ha
DAM
CREEK
PREVAILING WIND
2 km
RIVER
HOUSE COTTAGE CABIN
LAKE 160 ha
RIVER
DOWNSTREAM RECEPTOR

a particle size distribution of 50% less than 75 um; a pyrite content of 6.5%; a gypsum content of 5%; and, a radium concentration of 5 to 15 $Bq.g^{-1}$ distributed between the tailings solids and gypsum.

The reference receptor was chosen to be an adult male (i.e. Reference Man as defined in ICRP 23(1975)) living year-round in a cabin on the lake, shown on Figure C-1, some 2 km downwind of the reference tailings site. The receptor lives off the land deriving 50% of his food supply from local sources: eating vegetables and berries grown or harvested near the residence, eating fish taken from the lake, and eating game hunted in the immediate area. All his drinking water is taken from the lake and consumed directly without treatment for radium removal.

Potential exposure pathways considered in this study, for the reference receptor are shown on Figure C-2 and discussed in Sections 2.0, 3.0 and 4.0. The pathways modelled included the following components: the source (i.e. the tailings area); several environmental compartments; transfer models; and the receptor.

The concept of the pathways analysis presented on Figure C.2 is that the environment can be divided into a series of compartments (eg. air, surface water, fish) and that the contents of a compartment (eg. concentration, dose) can be calculated as a series of multiplicative steps. The total dose (final compartment) is determined by summing the estimated contributions from the individual pathways (eg. inhalation, ingestion of water). Symbolically, total dose X_{10}) is given as:

$$x_{10} = \sum_{ij} P_{ij}\, x_i \quad (\text{for } i=j)$$

FIGURE C·2

EXPOSURE PATHWAYS FOR REFERENCE RECEPTOR

NOMENCLATURE:

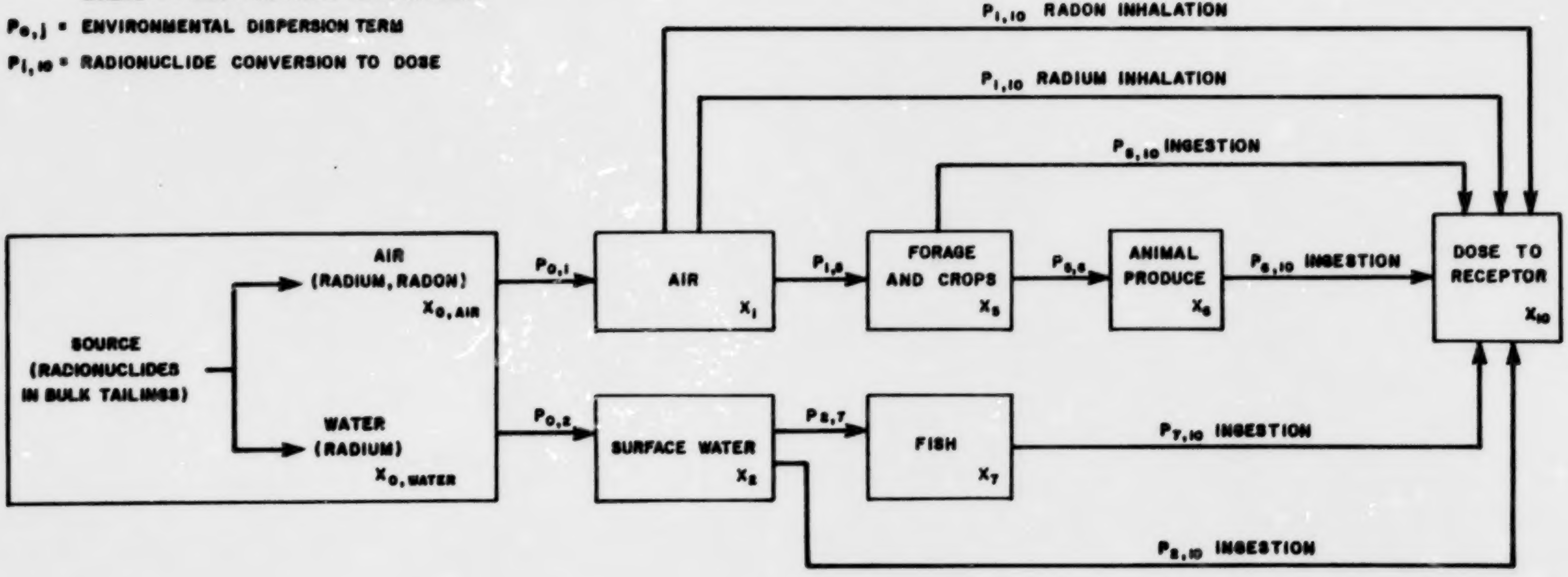
X_0 = APPROPRIATE SOURCE RELEASE RATE

X_j = CONCENTRATION OF RADIONUCLIDE IN ANY ENVIRONMENTAL COMPARTMENT $j = 1, 6$

$P_{i,j}$ = TRANSFER OF RADIONUCLIDE FROM COMPARTMENT i TO j WHERE i = ANY PREVIOUS COMPARTMENT

$P_{0,j}$ = ENVIRONMENTAL DISPERSION TERM

$P_{i,10}$ = RADIONUCLIDE CONVERSION TO DOSE


SOURCE (RADIONUCLIDES IN BULK TAILINGS)
AIR (RADIUM, RADON) $X_{0,AIR}$
WATER (RADIUM) $X_{0,WATER}$
$P_{0,1}$
$P_{0,2}$
AIR X_1
SURFACE WATER X_2
$P_{1,5}$
$P_{2,7}$
FORAGE AND CROPS X_5
FISH X_7
$P_{5,6}$
ANIMAL PRODUCE X_6
$P_{6,10}$ INGESTION
$P_{1,10}$ RADON INHALATION
$P_{1,10}$ RADIUM INHALATION
$P_{5,10}$ INGESTION
$P_{7,10}$ INGESTION
$P_{2,10}$ INGESTION
DOSE TO RECEPTOR X_{10}

where:

X_{10} = the total dose to the receptor via all pathways

X_i = the contaminant emission rate from the source term (X_o); or the environmental concentration in the atmosphere (X_1), surface water (X_2), forage or crop vegetation (X_5) animal (caribou) produce (X_6) or aquatic (fish) animals (X_7).

P_{ij} = the environmental dispersion terms from source to atmosphere ($P_{0,1}$), source to surface water ($P_{0,2}$); or alternatively the environmental transfer (conversion or distribution) terms from atmosphere to dose ($P_{0,2}$), atmosphere to vegetation $P(_{1,5})$, surface water to dose ($P_{5,10}$), animal produce to dose ($P_{6,10}$) or fish to dose ($P_{7,10}$).

Calculation of receptor exposure using the above equation requires the determination of approximate values for the source and enviormental compartments (i.e. the X_i blocks) and for the transfer terms (i.e. the $P_{i,j}$ lines).

In addition to the reference receptor, exposure to two additional receptors are also evaluated. First, a receptor living in the river-lake system further away from the tailings was modelled. This downstream receptor was developed to represent the characteristics of a more typical (than the reference receptor) member of the regional population. Secondly, potential exposure to an intruder, who is assumed to reside on the tailings was also estimated. Section 5.0 documents the characteristics of these two receptors and the exposure pathways considered for each.

The input parameters used in the calculations are presented in Section 6.0 and the methods used to calculate various consequences are described in Section 7.0.

2.0 ATMOSPHERIC PATHWAYS, COMPONENT MODELS FOR RADIUM

2.1 Source Term Model: $X_{o,air}$ Source to Air ($Bq.s^{-1}$)

EMIT = (RESFAC*RHOTAL*RESDEP)*RACNTA*HSUBD*WIND*$(AREA)^{1/2}$

where:

EMIT = source emission rate for $X_{o,air}$($Bq.s^{-1}$)
RESFAC = resuspension factor for dust from tailings (m^{-1})
RHOTAL = tailings density ($g.m^{-3}$)
RESDEP = effective resuspension depth (m)
RACNTA = radium concentration in tailings particles ($Bq.g^{-1}$)
HSUBD = initial mixing depth (m)
WIND = annual mean wind speed ($m.s^{-1}$)
AREA = effective tailings surface area (m^2)
= AREXTL* (1-COVER)

where:

AREXTL = exposed tailings surface area (m^2)
COVER = fraction of tailings vegetated
= EVENT + (0.9-EVENT) * (1-exp(-KRELAX*T))

where:

EVENT = fraction of tailings remaining vegetated immediately following an episodic event
KRELAX = constant based on time for tailings to return to approximately 90% cover (yr^{-1})
T = elapsed time from any episodic event (yr).

Derivation of $X_{o,air}$ (Radium)

The release rate for dust to the atmosphere (termed $X_{o,air}$) from the tailings surface is assumed to be solely a result of the action of wind on this surface. The source strength is directly dependent on the concentration of radium in that part of the tailings that is available for resuspension.

The source strength calculation is based on the resuspension factor approach (Gilbert 1983, Anspaugh 1975). If desired, the resuspension factor can be made time dependent (it is in fact time dependent but rapidly (<20 years) approaches an asymptotic value), and can be adjusted to account for catastrophic events which modify the tailings surface, such as a forest fire.
The resuspension factor is defined as

$$\mathrm{RESFAC} = \frac{\chi}{\mathrm{RHOTAL} * \mathrm{RESDEP}}$$

where:

χ = airborne dust concentration immediately above the tailings within the initial mixing depth ($g.m^{-3}$)
RESFAC = resuspension factor for dust from tailings (m^{-1})
RHOTAL = tailings density ($g.m^{-3}$)
RESDEP = effective resuspension depth (m)

The emission rate for radium in dust from the tailings surface is that given by Gilbert (1983):

$$\mathrm{EMIT} = \quad *\mathrm{RACNTA}*\mathrm{HSUBD}*\mathrm{WIND}*(\mathrm{AREXTL})^{1/2}$$

where:

EMIT = source emission rate ($Bq.s^{-1}$)
RACNTA = radium concentration in tailings particles ($Bq.g^{-1}$)
HSUBD = initial mixing depth (m)
WIND = annual mean wind speed ($m.s^{-1}$)

AREXTL = area of exposed tailings (m^2)

Combining the two equations leads to:

$$EMIT = RESFAC*RHOTAL*RESDEP*RACNTA*HSUBD*WIND*(AREXTL)^{1/2}$$

This approach to source term modelling is simple but still quite versatile. The frequency and intensity of high wind speeds is probably more important than the annual mean wind speed. However, a large amount of the uncertainty associated with the calculation is accommodated by the choice of distribution for the resuspension factor, RESFAC.

The structure of this model is such that time dependency in the source emission rate can be incorporated if desired. Two factors, AREXTL, the exposed tailings area, and RESFAC, the resuspension factor will vary with time. The exposed area will gradually decrease as vegetation covers the site.

In the present case, the undisturbed tailings (i.e. the null case) are assumed to be 90% vegetated. It is further assumed that the fraction of tailings vegetated will never exceed this level. The fraction of tailings vegetated would decrease to varying degrees depending on the nature of the particular episodic events (e.g. fire, drought or containment failure) being considered. Following any event, the vegetation would return to the 90% level over some period of time, depending on the nature of the particular event. Thus, vegetative cover can be modelled as:

$$COVER = EVENT + (0.9-EVENT) * (1-\exp(-KRELAX*T))$$

where:

EVENT = fraction of tailings remaining vegetated immediately following an episodic event

KRELAX = constant based on time for tailings to return to approximately 90% cover (yr^{-1})

T = elapsed time from any episodic event (yr)

Given the fraction of tailings which are vegetated, an effective surface area can be defined:

AREA = AREXTL * (1-COVER)

where:

AREA = effective tailings surface area exposed (m^2)

The resuspension factor, RESFAC will decrease with time, to an asymptote, as the tailings surface weathers. The small particles available for resuspension will gradually become depleted from the surface layer and RESFAC will decrease. Catastrophic events which disturb the surface layer and expose unweathered tailings may cause an increase in RESFAC. In the present analysis RESFAC is conservatively treated as an (uncertain) constant with no gradual change with time from its initial value.

2.2 Transfer Model: $P_{0,1}$ Atmospheric Transport (s.m^{-3})

$$P_{0,1}=2.032*FRACT*(WIND*DIST*SIGZED)^{-1}*EXP(-((HSUBD^2)*((2*SIGZED^2)-1)))$$

where:

$P_{0,1}$ = transfer factor for radium from the source via atmospheric transport (s.m^{-3})

FRACT = fraction of time the wind blows from source to receptor

WIND = wind speed (m.s^{-1})

DIST = downwind distance (m)

SIGZED = vertical dispersion coefficient (m)
HSUBD = initial mixing depth (source height) (m)

Derivation of $P_{0,1}$ Atmospheric Transport

The diffusion of material in the atmosphere as it is transported downwind from the source to the receptor is generally called dispersion. Because of its simplicity and widespread application (Hanna 1982, Turner 1967, U.S. NRC 1983) the sector averaged Gaussian plume model was chosen to model the dispersion from the tailings site. The equation is:

$$X = 2.032 \sum_{jk} \frac{n_{jk}}{N} \left[x \quad u_k \quad \sigma_{zj} \right]^{-1} \exp \left[\frac{-H^2}{2\, \sigma^2{}_{zj}} \right]$$

where:

X = the atmospheric concentration at the receptor
x = the downwind distance from the source to the receptor.
u_k = the wind speed of the kth class
σ_{zj} = the vertical diffusion parameter at downwind distance z and stability class j.
H = the height of release of the contaminant
k = wind speed class index
j = atmospheric stability class index
n_{jk} = length of time of the joint occurrence of wind speed class k, and stability class j, in a particular wind direction.
N = total length of time of observation

Assuming that the wind observations are reported for 16 sectors, the radium concentration in the atmosphere at the receptor can be calculated by the following simplified equation:

$$\text{RAAIR} = 2.032\text{*EMIT*FRACT*(DIST*WIND*SIGZED)}^{-1}\text{*exp} \left[- \frac{\text{HSUBD}^2}{2\text{*SIGZED}^2} \right]$$

where:

EMIT = the time rate of release of the contaminant (Bq.s^{-1})
FRACT =the fraction of time the wind blows in the sector of interest
WIND = is the mean wind speed in that sector (m.s^{-1})
DIST = the distance from source to receptor (m)
SIGZED = the stability class weighted average variance (m)
HSUBD = the pollutant release height, or the initial mixing depth (m)
RAAIR = the radium concentration in air at the receptor (Bq.m^{-3})

and the transfer factor can be found to be:

$$P_{0,1} = \frac{RAAIR}{EMIT}$$

The equations presented so far in this section are applicable to a point source. In the case of a tailings pile the actual source is not a point source but an area of finite size. In order to accommodate this area the concept of a virtual point source is used. A virtual point source is an imaginary point source located a distance upwind, such that the standard deviation of the plume from the imaginary source is matched to the width of the area source at the source. The virtual set back distance is a function of atmopsheric stability. For the reference tailings site it was calculated by assuming the source was 5×10^5 m^2 in area and was roughly circular. Then for each stability class a setback distance was calculated using well known procedures (Turner 1967). These distances were combined by taking an average, weighted by the percent frequency of occurrence of each stability class. Thus a mean setback distance of 1600 m was calculated. In all calculations involving DIST, a total distance of 3600 m was used, not the actual distance of 2000 m.

2.3 Transfer Model: $P_{1,5}$ Atmosphere to Vegetation ($m^3.g^{-1}$)

Airborne materials can be transferred to the edible portions of vegetables consumed by man or to forage consumed by animals via two mechanisms: direct foliar retention and root uptake. The transfer model used considers only the direct foliar retention. Root uptake was not modelled because of the relatively small contribution it makes to the total vegetation concentration.

Four categories of vegetation are considered: lichen (winter forage), summer forage, above ground vegetables and below ground vegetables.

The following equation is used (U.S. NRC 1982):

$$P_{1,5}=VELDEP*FDEPVE*ESUBV*\left[\frac{(1-\exp(-LAMWTH*TEXPDP)}{YDENST*LAMWTH}\right]$$

where:

VELDEP = the deposition velocity ($m.s^{-1}$)

FDEPVE =the fraction of the total deposition retained on the plant surface (0 to 1)

ESUBV = the fraction of the foliar deposition retained on edible portions of the vegetation (0 to 1)

LAMWTH = a decay constant accounting for weathering losses (s^{-1})

TEXPDP = the duration of plant exposure for vegetation type v to atmospheric deposition (s)

YDENST = the yield density for vegetation type v (g (wet wt).m^{-2})

2.4 Transfer Model: $P_{5,6}$ Vegetation to Animal Produce ($g.g^{-1}$)

Radionuclides deposited on winter (lichen) and summer (pasture) forage may be eaten by caribou which in turn may be eaten by man.

forage may be eaten by caribou which in turn may be eaten by man. The transfer of radionuclides from vegetation to meat was modelled as follows (U.S. NRC 1982):

$$P_{5,6} = QVEG*FETOPR*FVEGCN$$

where:

QVEG =intake of vegetation type v by animal type a (g(dry wt).a^{-1})

FETOPR = the feed-to-product (p) transfer coefficient for animal type a (Bq.g^{-1}.Bq^{-1}.a).

FVEGCN = the fraction of vegetation type v consumed by animal a that is local (0 to 1)

2.5 Transfer Model: $P_{5,10}$ Vegetation to Dose (Sv.a^{-1}.Bq^{-1}.g)

The annual dose due to ingestion of vegetation was calculated using the following transfer model (U.S. NRC 1982):

$$P_{5,10} = USUBV*DCFING*FVEGGR$$

where:

USUBV =the annual human ingestion rate of vegetation type v (g.a^{-1})

DCFING = dose conversion factor for ingestion (Sv.Bq^{-1})

FVEGGR =the fraction of vegetation type v grown at the contaminated source (0 to 1)

No correction was made for a reduction in the concentration of vegetables due to food preparation (such as washing, peeling and boiling).

2.6 Transfer Model: $P_{6,10}$ Animal Produce to Dose ($Sv.a^{-1}.Bq^{-1}.a$)

The transfer model for calculating annual dose due to the consumption of animal produce was (U.S. NRC 1982):

$$P_{6,10} = USUBP*DCFING*FSUBP$$

where:

USUBP = the annual human ingestion rate of animal produce type p ($g.a^{-1}$)

DCFING = dose conversion factor for ingestion ($Sv.Bq^{-1}$)

FSUBP = the fraction of animal produce that is contaminated (0 to 1)

2.7 Transfer Model: $P_{1,10}$ Atmosphere to Inhalation Dose (Particulate) ($Sv.a_{-1}.Bq_{-1}.m_3$)

The inhalation dose from radium in suspended particulate is calculated from the relationship:

$$P_{1,10} = OCCFAC*DCFINH*INHALE$$

where:

OCCFAC = occupancy factor or fraction of the year spent at that location (0 to 1).

DCFINH = dose conversion factor for the inhalation of radium ($Sv.Bq^{-1}$)

INHALE = annual inhalation rate ($m^3.a^{-1}$)

The dose conversion factor assumes particles with activity median aerodynamic diameters (AMAD) between 0.1 and 1.0 m (Johnson and Dunford 1983).

3.0 SURFACE WATER PATHWAYS: Component Models for Radium

3.1 Source Term Model: $X_{o,\mathrm{water}}$ Source to Water ($\mathrm{Bq.s^{-1}}$)

i) Radium Concentration in Tailings Porewater and Contaminated Runoff

$$\mathrm{RAPOWA} = \mathrm{RAGPTA}*0.1*\left\{\left[\mathrm{PHI}^2 + \frac{4*\mathrm{KSUBSO}}{\mathrm{FACTCO}^2}\right]^{1/2} - \mathrm{PHI}\right\} + \mathrm{RAEROS}$$

where:

RAPOWA = radium concentration in the tailings porewater ($\mathrm{Bq.m^{-3}}$)

RAGPTA = radium content of gypsum in the tailings ($\mathrm{Bq.mole^{-1}}$)

KSUBSO = solubility equilibrum constant for gypsum ($\mathrm{moles^2.m^{-6}}$)

FACTCO = activity coefficient:

for PHI>0.125, FACTCO=0.3

for $\mathrm{PHI} \leq 0.125$.

$$\mathrm{FACTCO} = \exp_{10}\left\{2.4*\left[\frac{\mathrm{PHI}}{1000}\right] - \left[\frac{4*(\mathrm{PHI}/1000)^{1/2}}{1 + 2*(\mathrm{PHI}/1000)^{1/2}}\right]\right\}$$

PHI = concentration of sulphates derived from pyrite oxidation ($\mathrm{moles/m^3}$)

$= 1.033*\mathrm{NPRCP}^{-1}*[(\mathrm{SULPRD}*\mathrm{RHOTAL}*\mathrm{O2CONC}*\mathrm{O2DIFF}*(1-\mathrm{KPRIME}*\ln((1+\mathrm{KPRIME})*\mathrm{KPRIME}^{-1}))]^{1/2}$

where:

NPRCP = net precipitation (i.e. after evapotranspiration losses) on tailings ($\mathrm{m.a^{-1}}$)

SULPRD = average yearly sulphate production rate ($\mathrm{moles\ .(g.a)^{-1}}$)

RHOTAL = tailings bulk density ($\mathrm{g.m^{-3}}$)

O2CONC = oxygen concentration at the tailings surface ($\mathrm{moles.m^{-3}}$)

O2DIFF = oxygen diffusivity through the tailings ($\mathrm{m^2.a^{-1}}$)

$\mathrm{KPRIME} = \dfrac{K_{02}}{\mathrm{O2CONC}}$

where:
K_{02} = half saturation constant for oxygen (moles.m^{-3})

RAEROS = Radium concentration in porewater due to soil erosion (Bq.m^{-3})
= RLOAD/(ARBASN*NPRCP*(1-FNPRCP))

where:
ARBASN = area of tailings basin watershed (m^{2})
NPRCP = net precipitation (m.a^{-1})
FNPRCP = fraction of net precipitation which enters groundwater flow
RLOAD = radium loading due to soil erosion (Bq.a^{-1})

$$= 30\mathrm{X}10^{6} * \mathrm{RACNTA} * \left\{ \frac{-.3375 * \mathrm{COVER} + .33375}{.03} \right\}$$

where:
RACNTA = radium concentration in bulk tailings (Bq.g^{-1})
COVER = fraction of tailings vegetated (varies with time and event)

ii) Source Term Emission Rate for Radium and Surface Water $(X_{o,water})$

XOSWRA = RAPOWA*NPRCP*(1.0-FNPRCP)*ARBASN* ((3.1536x10^{7})$^{-1}$)

iii) Source Term Emission Rate for Radium in Groundwater $(X_{o,water})$

XOGWRA = = RAPOWA*NPRCP*FNPRCP*ARBASN* ((3.1536x10^{7})$^{-1}$)

where:

FNPRCP = fraction of precipitation on the tailings drainage basin that infiltrates and enters the deep groundwater flow below the tailings.

ARBASN = area of the tailings basin watershed (m^2)

XOSWRA= source term emission rate for radium in surface water ($Bq.s^{-1}$)

XOGWRA= source term emission rate for radium in groundwater ($Bq.s^{-1}$)

Derivation of $X_{o,water}$ (Radium)

Development of a preliminary source term model which describes the mobilization of radium from uranium tailings was undertaken specifically for pyritic tailings undergoing oxidation of the pyritic fraction. Much of the readily leachable radium is present in slightly soluble co-precipitates, such as gypsum ($CaSO_4.2H_2O$), that formed either during tailings neutralization with lime, or by secondary mineralization in the tailings basin. From the leaching studies of Silver and Ritcey (1980), it is estimated that 25% to 50% of the total radium present in tailings is contained in the potentially leachable fraction of the tailings solids. Tailings typically contain approximately 5% gypsum (as $CaSO_4$).

-In the preliminary source term model, the concentration of radium in the porewater below the tailings surface is calculated as a function of the concentration of (dissolved) gypsum in the same porewater. Since the molar concentration of gypsum will be approximately equal to the molar concentration of calcium, the radium concentration can be expressed as:

$$[Ra^{2+}] = K[Ca^{2+}]$$

where:

[ ]= concentration of dissolved ions (moles.m^{-3})

K = proportionality constant (equal to the concentration of Ra^{2+} in gypsum)

The solubility of gypsum, and hence the concentration of Ca^{2+} is dependent on the solubility product as follows:

$$\frac{KSUBSO}{\left[f_{Ca^{2+}}\right]\left[f_{SO_4^{2-}}\right]} = [SO_4^{2-}]\ [Ca^{2+}]$$

where:

KSUBSO = solubility equilibrium constant (25.0 $moles^2.m^{-6}$)

$f_{Ca^{2+}}$ = activity coefficient (calcium ion)

$f_{SO_4^{2-}}$ = activity coefficient (sulphate ion)

The activity coefficients, assumed to be essentially equal, can be estimated from the Davies equation (Stumm and Morgan 1981):

$$\log FACTCO = -AB^2 \left\{ \frac{(I)^{1/2}}{1 + (I)^{1/2}} - 0.3I \right\}$$

where:

FACTCO = activity coefficient (f)

I = ionic strength of the solution

A = $1.82 \times 10^6 (T)^{-1.5}$ (dielectric constant of water)

B = ionic charge

At 10° C (283.K) the value of 'A' in the above equation is 0.5 (dielectric constant = 83.95)

The ionic strength (I) can be calculated from:

$$I = 1/2 \sum_i C_i z_i{}^2$$

where

C_i = concentration of ith ionic species

z_i = ionic charge of the ith species

Assuming an equal content of divalent cations and anions, with the sulphate ion being the predominant anion, it can be shown that:

$$I = 4^{*}[SO_4{}^{2-}]$$

Substituting these values into the expression for calculating the activity coefficients (i.e. the Davies equation) for divalent ions

$$FACTCO = \exp_{10} \quad 2.4[SO_4{}^{2-}] - \frac{4[SO_4{}^{2-}]^{1/2}}{1+2[SO_4^{2-}]^{1/2}}$$

In theory, the sulphate concentration in the above equation should include sulphate resulting from both pyrite oxidation and gypsum dissolution. Since the solubility of gypsum is dependent on the activity coefficient, the calculation procedure should be iterative. Recognizing that pyrite oxidation is the major source of sulphate, the ionic strength is assumed to be numerically equal to twice the ionic strength resulting from sulphate production by pyrite oxidation. Although this gives an approximate value for the activity coefficient, it avoids the use of cumbersome trial and error methods to calculate the activity coefficient.

It may be assumed that the limestone ($CaCO_3$) content (up to 1%) of pyritic tailings is rapidly depleted due to acid generation resulting from pyrite oxidation above the water table. Thus, the dissolution of gypsum is the major source of calcium during the initial years. On the other hand, pyrite oxidation of tailings contributes significantly to the sulphate concentration in the porewater. That is:

$$[Ca^{2+}] = [Ca^{2+}]_g$$
$$[SO_4{}^{2-}] = [SO_4{}^{2-}]_g + [SO_4{}^{2-}]_p$$

where:

$[C_a{}^{2+}]_g$ = calcium derived from dissolution of gypsum
$[SO_4{}^{2-}]_g$ = sulphate derived from dissolution of gypsum
$[SO_4{}^{2-}]_p$ = sulphate derived from pyrite oxidation (PHI)

In the relationships expressed above:

$$[Ca^{2+}]_g = [SO_4{}^{2-}]_g$$

hence, substituting into the equation given previously for the solubility product, the following expression is obtained:

$$\frac{\text{KSUBSO}}{\left[f_{Ca^{2+}}\right]\left[f_{SO_4^{2-}}\right]} = ([SO_4{}^{2-}]_p + [SO_4{}^{2-}]_g)\ [Ca^{2+}]_g$$

or

$$\frac{\text{KSUBSO}}{\left[f_{Ca^{2+}}\right]\left[f_{SO_4^{2-}}\right]} = [SO_4{}^{2-}]_p * [Ca^{2+}]_g + [Ca^{2+}]_g{}^2$$

solving this equation for $[Ca^{2+}]$ gives:

$$[Ca^{2+}] = 0.5*\left\{\sqrt{[SO_4{}^{2-}]_p^2 - [4\ \text{KSUBSO} \div \left[f_{Ca^{2+}}\right]\left[f_{SO_4^{2-}}\right]} - [SO_4{}^{2-}]_p\right\}$$

To solve for the activity coefficient (FACTCO), the sulphates derived from pyrite oxidation must be quantified. The derivation of this quantity depends on a wide variety of physical factors as outlined below.

In pyritic tailings it is convenient to distinguish between the oxygenated zone, comprising the tailings in contact with oxygen, and a redox zone, where chemical reactions proceed in the absence of oxygen. The latter region is influenced by the export products of the overlying oxygenated zone.

The overall oxidation rate (in terms of sulphate generation) is governed by the diffusion of oxygen. The stoichiometry of the oxidative process is as follows (Nordstrom 1982):

$$2\ FeS_2 + 7.5\ O_2 + 7\ H_2O \rightleftharpoons 2\ Fe(OH)_3\ (s) + 8\ H^+ + 4\ SO_4^{2-}$$

The differential equation describing the oxygen concentration at some depth "z" in the tailings, neglecting oxygen transport by barometric or hydraulic "pumping", is given by (Halbert et al 1983):

$$\frac{\partial C_{(z,t)}}{\partial t} = \mathrm{O2DIFF}\frac{\partial^2 C_{(z,t)}}{\partial z^2} - \frac{7.5}{4}\ \mathrm{*SULPRD*RHOTAL}$$

where:

$C_{(z,t)}$ = oxygen concentration at depth "z" (moles.m^{-3})
O2DIFF = oxygen diffusivity through tailings ($m^2.a^{-1}$)
SULPRD = sulphate production rate (moles.$(g.a)^{-1}$)
RHOTAL = tailings bulk density (g.m^{-3})
z = depth into the tailings from the surface (m)

For any value of oxygen demand (ie. SULPRD*RHOTAL*7.5/4 > 0), the oxygenated zone in the tailings develops to a finite thickness, λ. Two solutions of the differential equation are as follows.

i) for initial conditions $C_{(z,o)} = 0$;

$$\frac{C_{(z,t)}}{C_{(o,t)}} = 1 - \frac{z}{\lambda}^{2} - \mathrm{erf}\left[\frac{z}{2^*(O2DIFF^*t)^{1/2}}\right]$$

ii) for initial conditions $C_{(z,o)} = C_{(o,t)}$ and $0 \leq z \leq \lambda$;

$$\frac{C_{(z,t)}}{C_{(o,t)}} = \left[1 - \frac{z}{\lambda}\right]^{2} + \frac{32}{3\pi} \sum_{n=1}^{\infty} \frac{1}{n^{3}} \sin\left[\frac{n\pi}{2}\left(\frac{z}{\lambda}\right)\right] \exp\left[-\left(\frac{n\pi}{2\lambda}\right)^{2} {}^*O2DIFF^*t\right]$$

where:

$C_{(o,t)}$ = oxygen concentration at the interface (moles.m^{-3})

λ = steady state thickness of the oxygenated zone (m)

erf = the error function

The thickness, λ, is determined from steady state conditions ($\partial C_{(z,t)}/\partial t = 0$):

$$\lambda = \left[\frac{8}{7.5}\,\frac{C_{(o,t)}{}^*O2DIFF}{SULPRD^*RHOTAL}\right]^{1/2}$$

The pyrite oxidation rate (SULPRD), is dependent on a number of variables including the pyrite content, the particle surface area, moisture content, temperature, pH, and oxygen concentration. Although all of these variables may be included in a comprehensive model, in the present case only the dependence on temperature, moisture content and oxygen concentration are considered. The temperature dependence is evaluated by selecting a typical monthly soil temperature distribution and calculating the yearly average oxidation rate as follows:

$$SULPRD = \sum_{i=1}^{12} R_{so} \exp\left[\frac{\Delta E_a}{R\ T_o} - \frac{\Delta E_a}{R\ T_i}\right]$$

where:

SULPRD = average yearly sulphate production rate as SO^{2-} (moles.g^{-1}.a^{-1})

R_{so} = monthly sulphate production rate as SO_4^{2-} at reference temperature (moles .g^{-1}.$month^{-1}$)

ΔE_a = activation energy of pyrite oxidation (25.6 kcal.(mole. K)$^{-1}$)

R = the universal gas constant (1.987 cal.mole^{-1})

T_o = reference temperature (293 K)

T_i = soil temperature in the "i"-th month (K)

The effect of moisture content on SULPRD is obtained by appropriate adjustment of the reaction rate under unsaturated conditions.

The effect of oxygen concentration on the reaction rate (SULPRD) can be described by the following equation (Shumate et al 1971):

$$R_s^* = SULPRD^* \left[\frac{C(z,t)}{K_{O2} + C(z,t)} \right]$$

where:

K_{O2} = half saturation constant for oxygen (moles.m^{-3})

R_s^* = average yearly sulphate production rate adjusted for the effect of oxygen concentration (moles.g^{-1}.a^{-1})

The numerical solution of the model requires an estimate of the diffusivity coefficient of oxygen through the tailings. In the present case, the following expression is used:

$$O2DIFF = D_o \frac{\varepsilon_a}{\varepsilon_p} \left[\varepsilon_p \right]^{1.5}$$

where:

O2DIFF = diffusivity coefficient of oxygen in unsaturated tailings ($m^2.a^{-1}$)

D_o = diffusivity coefficient of oxygen in air ($m^2.a^{-1}$)

ε_a = airspace porosity at given moisture content

ε_p = porosity (total)

Although transient solutions have been developed for various initial conditions, only the steady state solution is considered at the present. It can be shown that the steady state sulphate generation flux derived from the oxygen flux into the tailings is given by:

$$J_s = \left\{ \frac{8}{7.5} * SULPRD * RHOTAL * O2CONC * O2DIFF * \left[1 - KPRIME * \ln \left(\frac{1+KPRIME}{KPRIME} \right) \right] \right\}^{1/2}$$

where:

J_s = the steady state sulphate flux ($moles.m^{-2}.a^{-1}$)

KPRIME = $K_{O2}/O2CONC$

The sulphate concentration due to pyrite oxidation is thus:

$$PHI = \frac{J_s}{NPRCP} = [SO_4^{2-}]_p$$

where:

NPRCP = net precipitation (i.e. after evapotranspiration losses) on the tailings basin ($m.a^{-1}$)

PHI = concentration of sulphate in the tailings porewater ($moles.m^{-3}$)

Hence, the expression given previously for calculating [Ca^{2+}] can be solved and the radium concentration in porewater can be determined from:

$$\text{RAPOWA} = \text{K*0.5*}\left\{\left(\text{PHI}^2 - \frac{\text{4*KSUBSO}}{\text{FACTO}^2}\right)^{1/2} - \text{PHI}\right\}$$

K = Ra content of gypsum = RAGPTA
  = 6.8 x 10^4 to 2.7 x 10^5 pCi*mole^{-1}
  = 2,500 to 10,000 Bq*mole^{-1}

The equation above applies if the dissolution of gypsum containing the radium is congruent, i.e. if the molar (or mass) ratio of radium to calcium in the liquid phase (porewater) and the solid phase are identical. However, observed concentrations of radium range from 60 to 240 pCi*L^{-1} in tailings porewater in the Elliot Lake region (Golders Associates 1981a and 1981b, Cherry et al 1980, Blair et al 1980). These porewaters are essentially saturated with respect to gypsum, the calcium ion concentration being 1 x 10^{-2} M to 1.5 x 10^{-2} M. The observed ratios of Ra^{2+} to Ca^{2+} in the porewater were 6,000 pCi*mole^{-1} to 23,000 pCi*mole^{-1}. These ratios are in sharp contrast to Ra^{2+} to Ca^{2+} ratios of 68,000 to 270,000 pCi*mole^{-1} in the bulk solid phase (gypsum). It appears that the dissolution process is incongruent, resulting in an enrichment of the gypsum surface with radium. Consequently, it appears that the Ra^{2+} to Ca^{2+} ratio in the porewater is attentuated with respect to the bulk solid phase. The resultant attentuation factor, expressed as the ratio of the radium content in the liquid phase to the solid phase may range from 0.005 to 0.34. For the purposes of the Phase I probabilistic analysis, an attentuation factor of 0.2 was used. This attentuation factor acts as a direct multiplier in the calculation of the radium concentration in porewater. Hence, the expression give above becomes:

$$\text{RAPOWA} = \text{0.2* RAGPTA*0.5*}\ \ \text{PHI}^2 - \left\{\left(\frac{\text{4*KSUBSO}}{\text{FACTCO}^2}\right)^{1/2} - \text{PHI}\right\}$$

$$RAPOWA = 0.1*RAGPTA* \quad PHI^{2} - \frac{4*KSUBSO}{FACTCO^{2}}^{1/2} - PHI$$

As well, there is additional Radium loading due to surface erosion by water. This is determined using the soil loss equation: (NUREG/CR-3144)

$$A = R*K*L*S*C*P$$

where:

A = soil loss (standard tons/acre.yr)
R = rainfall and runoff index
L = slope length factor
S = slope steepness factor
C = cover factor
P = practice factor

Some parameter values can be estimated using the information in Tables 27, 28 and 29A, NUREG/CR-3144.

R = 100 for central/southern Ontario (Figure 29)
L x S = 0.3 (from Table 28 slope 0.5-1%)
K = 0.3 (from Table 27 (range .14-.6))
C = .01 for grass and legume in formal application (say .03 for tailings field)
P = 1 by definiton (no practice)

Therefore, soil loss can be calculated for a covered field:

A = 100 x 0.3 x 0.3 x .03 x 1
= 0.27 t/a/acres
= 0.61 tonnes/ha/a

Thus, for 50 ha site:

Total loss = 0.61 x 50 = 30 t/a
RLOAD = $30 * 1 \times 10^{6} *$ RACNTA

where:

RLOAD = radium loading due to soil erosion ($Bq.a^{-1}$)

RACNTA = Radium concentration in tailings ($Bq.g^{-1}$)

The COVER factor C varies on the basis of vegetative cover (as defined previously):

at 90% coverage; C = 0.03

at 10% coverage; C = 0.3

The equation developed above is valid for 90% coverage (C=.03). A correction factor can be devised assuming a linear relationship between percent coverage and cover factor. The corrected equation is then:

$$\text{RLOAD} = 30 * 10^6 * \text{RACNTA} * \left\{ \frac{-.3375 * \text{COVER} + .33375}{.03} \right\}$$

This loading (in Bq/year) must then be converted to a porewater concentration, using drainage basin volumetric flow information. The porewater concentration of radium due to erosion is thus:

RAEROS = RLOAD/(ARBASN*NPRCP*(1-FNPRCP))

where:

RAEROS = radium concentration in porewater due to erosion ($Bq.m^{-3}$)

RLOAD = radium loading due to erosion ($Bq.a^{-1}$)

ARBASN = area of the tailings basin watershed (m^2)

NPRCP = net precipitation ($m.a^{-1}$)

FNPRCP = fraction of net precipitation which enters groundwater flow.

Thus, the total loading of radium to tailing porewater is:

$$RAPOWA = 0.1 * RAGPTA * \left\{ \left(\frac{PHI^2-4*KSUBSO}{FACTCO^2} \right)^{1/2} - PHI \right\} + RAEROS$$

3.2 Transfer Model: $P_{0,2}$ Source to Surface Water ($s.m^{-3}$)

The transfer model for contaminated surface runoff from the tailings drainage basin initially involves mixing with freshwater flow in a river located some 200 m from the reference site. Additional mixing with freshwater occurs as the river flow moves downstream. The river discharge is further diluted in a lake situated some 2 km downstream of the reference site. Radium removal on suspended inorganic solids and sorption onto biomass occurs in the lake with subsequent deposition to the bottom sediments. These model components are discussed in turn below.

i) River System Component

$$RARTOT = \frac{(RAPOWA*ARBASN*NPRCP*(1.0-FNPRCP))+JFLUX+QSUBI*RATI}{(ARBASN*NPRCP*(1.0-FNPRCP))+QSUBI}$$

where:

RARTOT = concentration of radium in the river at its discharge into the lake ($Bq.m^{-3}$).

RAPOWA = radium concentration in the tailings porewater ($Bq.m^{-3}$)

ARBASN = area of the basin the tailings are located in (m^2)

NPRCP = net precipitation on the tailings ($m.a^{-1}$)

QSUBI = flowrate of the freshwater in the river system, at the point of discharge to the lake, excluding the tailings area discharge. For a net watershed area of 13.5×10^6 m^2 QSUBI was calculated from the relationship NPRCP x 13.5E6(m^3a^{-1})

RATI = concentration of Ra-226 in the river system, upstream of the tailings discharge ($Bq.m^{-3}$)

FNPRCP = fraction of net precipitation (NPRCP) that flows to the river via the groundwater route

JFLUX = contaminant flux via the groundwater route to the river (set equal to zero for the time frame considered in this analysis) ($Bq.a^{-1}$)

This model simply weights the inputs to the river system to arrive at a volume weighted concentration at the mouth of the river just upstream of the lake. When the water leaves the river and enters the lake, it is mixed and portioned into various components.

ii) Lake System Component

$$\mathrm{RALTOT} = \frac{\mathrm{QSUBR*RARTOT/ARLKBT+JRAWCO}}{\frac{\mathrm{QSUBO}}{\mathrm{ARLKBT}} + \frac{\mathrm{SIGSS*KSUBD*SSL+SIGBIO*KSUBBI*BIOWCL}}{\mathrm{1+KSUBD*SSL+KSUBBI*BIOWCL}}} + [\mathrm{RALOAD*exp(-RESTIM*T)}]$$

where:

RALTOT = total Radium-226 in the lake water column ($Bq.m^{-3}$)

QSUBR = total flow in the river, at the discharge to the lake including the tailings sub-basin discharge. For a total watershed area of 15.0×10^6 m^2 QSUBR was calculated as NPRCP x 15E6 in the model ($m^3.a^{-1}$)

RARTOT = total radium concentration in the river at the point of discharge into the lake ($Bq.m^{-3}$)

ARLKBT = total area of the lake bottom (m^2)

QSUBO = total water outflow from the lake. For a total watershed area of 20.0×10^6 m^2, QSUBO was calculated as NPRCP x 20E6 in the model ($m^3.a^{-1}$)

SIGSS = sedimentation velocity of suspended solids ($m.a^{-1}$)

KSUBD = sorption coefficient for radium onto suspended solids ($m^3.g^{-1}$)

SIGBIO = sedimentation velocity of biomass ($m.a^{-1}$)

KSUBBI =transfer coefficient for radium to aquatic organisms ($m^3.g^{-1}$)

RALOAD = concentration of radium resulting from a shock load ($Bq.m^{-3}$)

RESTIM = decay constant based on lake residence time. (a^{-1})

T = elapsed time from any shock load (a).

The suspended solids level in the water column is calculated as follows:

$$SSL = QSUBR*SSR/(ARLKBT*SIGSS + QSUBO)$$

where:

SSL = concentration of suspended solids in the water column ($g.m^{-3}$)

SSR = concentration of suspended solids in the river discharge to the lake ($g.m^{-3}$)

The biomass level in the water column is calculated as follows:

$$BIOWCL = PROBIO/(SIGBIO + QSUBO/ARLKBT)$$

where:

BIOWCL = concentration of aquatic biota in the lake water column ($g.m^{-3}$)

PROBIO = net biomass productivity ($g.m^{-2}.a^{-1}$)

The radium flux from the bottom sediment into the water column (JRAWCO) is calculated as follows:

$$JRAWCO = \frac{KSUBL*QSUBR*RARTOT*((ZETA-1)+ZETA1*\exp(-DECAY*T))}{QSUBO*(1 + KSUBBI*BIOWCL + KSUBD*SSL)}$$

where:

KSUBL = mass transfer coefficient of radium into the water column from the sediments ($m.a^{-1}$)

ZETA = concentration ratio of dissolved radium between the interstitial sediment water and the lake water.

ZETA1 = concentration ratio for a shock loading of radium

DECAY = decay constant for flux due shock load (a^{-1})

T = elapsed time from any shock load (a)

JRAWCO = flux of radium from the sediments into the water column ($Bq.m^{-2}.a^{-1}$)

Finally it is necessary to calculate the transfer coefficient, as follows:

$$P_{0,2} = RALTOT/XOSWRA$$

3.3 Transfer Model: $P_{2,7}$ Surface Water to Aquatic Animals $(m_2.g_{-1})$

A simple transfer coefficient was used to model the concentration in edible portions of locally available aquatic animals as follows (U.S. NRC 1982):

$$P_{2,7} = BFRA$$

where:

BFRA = water to edible portion of aquatic animal type f transfer coefficient ($Bq.g^{-1}.Bq^{-1}.m^3$)

3.4 Transfer Model: $P_{7,10}$ Aquatic Animal to Dose $(Sv.a_{-1}.Bq_{-1}.g)$

The annual dose received by an individual as a result of eating aquatic animals was modelled using the following parameters (U.S. NRC 1982).

$$P_{7,10} = USUBA*DCFING*FSUBA$$

where:

USUBA = the annual human ingestion rate of aquatic animal type f $(g.a^{-1})$

DCFING = dose conversion factors for ingestion $(Sv.Bq^{-1})$

FSUBA = the fraction of aquatic animal type f that is contaminated (0 to 1)

3.5 Transfer Model: $P_{2,10}$ Surface Water to Dose (Ingestion) $(Sv.a_{-1}.Bq_{-1}.m_3)$

The annual dose due to ingestion of surface water was modelled as (U.S. NRC 1982):

$$P_{2,10} = USUBW*DCFING*FWATHM$$

where:

USUBW = the annual human intake of water $(m^3.a^{-1})$

DCFING = dose conversion factor for ingestion $(Sv.Bq^{-1})$

FWATHM = the fraction of water consumed by a human that is contaminated (0 to 1)

4.0 ATMOSPHERIC PATHWAYS: Component Models for Radon

4.1 Source Term Models for Radon: $X_{o,air}$ Source Emission Rate $(Bq.s_{-1})$

RNSOUR = ARTLSR*RACNTA*LAMRN*EMANAT*LSUBT*RHOTAL*
((NSUBW*WTSFLX+(12-NSUBW))/12)*exp(-1*(THICK/LSUBC))

where:

RNSOUR = source emission rate of radon, $X_{o,air}$ $(Bq.s^{-1})$
ARTLSR = total tailings surface area (m^2)
RACNTA = radium concentration in the tailings $(Bq.g^{-1})$
EMANAT = emanation coefficient
RHOTAL = tailings bulk density $(g.m^{-3})$
LAMRN = radioactive decay constant for radon (s^{-1})
LSUBT = radon diffusion length in tailings (m)
THICK = clean cover thickness (m)
LSUBC = radon diffusion length in the cover (m)
NSUBW = number of winter months (freezing conditions) per year
WTSFLX = winter-to-summer radon flux ratio (dimensionless)

The radon diffusion length, LSUBT, in tailings may be calculated as follows:

LSUBT = $(D/(LAMRN*P))^{1/2}$ (m)
= $(EBKDFC/LAMRN)^{1/2}$

where:

P = porosity of tailings
EBKDFC = effective bulk diffusion coefficient for radon $(m^2.s^{-1})$
= $P*0.106 \times 10^{-4}$ exp (-0.261*MPCH2O)
MPCH2O = percent water (by weight) in tailings
D = bulk diffusion coefficient of radon $(m^2.s^{-1})$

Derivation of the Radon Source Term, $X_{o,air}$

The following describes a model for the simulation of the rate of release of radon from uranium mill tailings. This release rate is used as the source term in the air dispersion model that calculates radon concentration in air attributable to the tailings at the receptor location. The theory of radon release is well presented in many publications and is not discussed in detail here. For example, the reader may refer to the U.S. NRC's Final Generic Environmental Impact Statement on Uranium Milling (U.S. NRC 1980) for further information or to Chambers et.al (1980) for the modelling of radon source terms in the context of Canadian uranium tailings areas.

The radon flux or rate of radon release from the surface of a tailings pile to the atmosphere is dependent on several factors including: the rate at which radon is produced through the decay of the parent radium; the fraction of radon which escapes the solid matrix in which it was formed and enters the tailings pore space (the emanation coefficient); and the rate at which the radon in the pore space (interstitial radon) migrates to the tailings surface. Radon migration is in turn dependent on both diffusion and transport (ie. bulk flow) phenomena. In the following discussions, the tailings pile is considered to be homogeneous with respect to radium content, water content and particle size, and infinitely deep (>3 to 4 m) in terms of radon diffusion. Although in practice differential settling of tailings particles after discharge to a tailings pile may occur and radium concentration may be a function of particle size, the distinctions are minor relative to the accuracy of the radon model which attempts to predict the overall average (over a year) rate of release of radon from the tailings pile.

i) Radon Production

The radon production rate (q) in a porous radium-bearing material can be expressed as:

$$q = RACNTA*RHOTAL*EMANAT*LAMRN/P$$

where:

q = radon production rate (Bq.s^{-1}.m^{-3} of pore space)
RACNTA = tailings radium concentration (Bq.g^{-1})
RHOTAL = tailings density (g.m^{-3})
EMANAT = emanation coefficient
P = porosity of tailings
LAMRN = radon decay constant ($2.1 \times 10^{-6} s^{-1}$)

The emanation coefficient, EMANAT, varies widely but a typical value of 0.2 has often been used to model radon releases from tailings.

ii) Radon Diffusion

The diffusion of radon through a homogeneous, porous medium can be modelled using classical diffusion theory. The one-dimensional equation for the radon concentration in a tailings pile is:

$$\frac{\partial C}{\partial t} = \frac{D}{P} * \frac{\partial^2 C}{\partial x^2} - C*LAMRN + B$$

where:

C = radon concentration (Bq.m^{-3} of pore space)
D = bulk diffusion coefficient (m^2.s^{-1})
B = radon source strength (Bq.s^{-1}.m^{-3})
X = distance (m)
P = porosity of tailings
LAMRN = radon decay constant (s^{-1})

The term D/P can be called the effective diffusion coefficient (EBKDFC). Short term variations in the transport of radon (as opposed to pure diffusion) through the tailings that are caused by pressure, windspeed, and temperature fluctuations are often included in the measured values of EBKDFC.

iii) Radon Flux

The steady-state condition ($\partial C/\partial t = 0$) can be solved to give the radon flux J_o at the surface of the tailings:

$$J_o = RACNTA*EMANAT*RHOTAL*LAMRN*LSUBT$$

where:

J_o = radon flux at the tailings surface ($Bq.m^{-2}.s^{-1}$)

LSUBT = radon diffusion length in tailings (m)
= $(EBKDFC/LAMRN)^{1/2}$

and the other terms are as previously defined.

The diffusion of radon in tailings is greatly affected by the moisture content of the tailings. The radon flux from water-saturated tailings can be lower by a factor of 100 or more relative to the radon flux from dry tailings. A reasonable empirical correlation between the effective diffusion coefficient and moisture content (Rogers et al 1980) is:

$$EBKDFC = P*0.106 \times 10^{-4} \exp (-0.261*MPCH2O)$$

where:

MPCH2O = percent moisture content (by weight)

P = porosity of tailings

More complex empirical relationships between moisture content and diffusion have been derived but their use is not required here to demonstrate the overall probabilistic modelling technique.

iv) Exhalation from Covered Tailings

The flux (J) of radon through a covered tailings pile can be approximated by:

$$J = J_o \exp (THICK/LSUBC)$$

where:

Jo = radon flux at tailings surface ($Bq.m^{-2}.s^{-1}$)

THICK = cover thickness (m)

LSUBC = diffusion length of radon in cover (m)
= $(DC/LAMRN)^{1/2}$

DC = effective diffusion coefficient in cover material ($m^2.s^{-1}$)

and it is assumed that the cover contains no radium. LSUBC for typical soils ranges from 0.5 to 1.5 m.

v) Winter/Summer Correction

The previous discussions have been concerned with radon flux from tailings under normal conditions. However, freezing conditions and snow cover greatly attenuate the radon flux because of the much smaller diffusion coefficient of ice relative to water. The effect is dependent on the moisture content of the tailings (Zettwoog et al 1981). This effect can be accommodated by using a seasonally-weighted average for radon flux and a winter/summer flux ratio. The annual average flux J_{AVG} is then given by:

$$J_{AVG} = J_s \, [NSUBW*WTSFLX + (12-NSUBW)]/12$$

where:

J_s = summer flux ($Bq.m^{-2}.s^{-1}$)
NSUBW = number of winter months (freezing conditions) per year
WTSFLX = winter/summer flux ratio
= 0.02 nominally (Zettwoog et al 1981)

4.2 Transfer Model $P_{0,1}$ Source to Atmosphere ($s.m^{-3}$)

The source-to-atmosphere transfer terms for particulate matter or radon are the same. In developing the transfer model, it was assumed that the materials being dispersed were of neutral buoyancy; generally a good approximation for both radon and the particulate matter released from tailings.

4.3 Transfer Model $P_{1,10}$ Atmosphere to Inhalation Dose (Radon) ($Sv.a_{-1}.Bq_{-1}.m_3$)

The inhalation dose from radon is calculated from the relationship:

$$P_{1,10} = OCCFAC*DCFIRN$$

where:

OCCFAC = occupancy factor or fraction of the year spent at that location (0 to 1)
DCFIRN = dose conversion factor for the inhalation of radon (= 7.2×10^{-5} $Sv.a^{-1}.Bq^{-1}.m^3$)

The dose conversion factor assumes a radon daughter/radon equilibrium factor of 0.5, and a dose equivalency of 4.8 WLM and 0.05 Sv.

5.0 DETAILS OF RECEPTORS MODELLED

5.1 Reference Receptor

The models just presented, and input parameter values outlined in section 6.0 apply strictly to a receptor residing in a cabin on a nearby lake, consuming all of his water and much of his food from local sources. This was the so-called "reference receptor" from an earlier study (SENES, 1984), as described in Section 1.0.

5.2 Downstream Receptor

It was considered appropriate to model a receptor somewhat farther away from the tailings than the first receptor, and having more moderate living habits. Such a downstream receptor is likely more representative of the average individual in the region around the tailings site. No changes to the models presented earlier were necessary to simulate the effects on this "downstream receptor", however, several input parameter values were altered. These changes, reflecting a receptor 10 km from the tailings, are summarized below.

i) drinking water source now considered to be a river. Lake radium concentration was diluted by a factor of 10 to arbitrarily simulate downstream radium concentration.

ii) atmospheric dispersion ($P_{o,1}$)
DIST changed from 3600 to 11,000 m
SIGZED changed from lognormal (70,1.73) to lognormal (140,1.73)

iii) human intake of fish:
FSUBA changed from 1.0 to 0.5

5.3 Tailings Intruder

A third receptor considered was a hypothetical individual residing directly on the tailings. The primary exposure pathways of this individual are likely quite different from those considered earlier. The individual is likely to receive a radiation dose while outdoors on the (uncovered) tailings surface and is also likely to be exposed to high levels of radon while inside his dwelling. These two pathways result in doses several orders of magnitude greater than any predicted using the pathways models described earlier.

i) Direct Exposure

assume:
time indoors = 14 hrs/day
time outdoors = 10 hrs/day
and
shielding factor for time indoors = 0.825

Then the total effective fraction of the day exposed is:

$$\frac{14}{24} * 0.825 + \frac{10}{24} = 0.9$$

and total hours per year exposed is:

$$OCCFAC*0.9*8760 = 7.86E3 *OCCFAC$$

where:
OCCFAC = occupancy factor (as defined previously)

For an exposure rate of the order of 0.5E-5 Sv/a per Bq/g the annual external exposure (DOSEXT) is:

DOSEXT = 3.93E-2*OCCFAC*RACNTA

(after Chambers et. al 1981)

where:

RACNTA = radium concentration in tailings (Bq^{-1})

ii) Radon Inhalation

The calculation of radon concentration inside the receptor's dwelling requires several assumptions regarding the dimensions and configuration of the structure. Assume:

dimensions = 10m x 6m x 5.5m (total height)

depth below grade = 1.5m

(i.e. height above grade = 4.0m)

Then, radon concentration inside the structure (C) is given by:

$$C = \frac{O\ AB}{V} \qquad (Bq.m^{-3})$$

where:

= radon flux from tails ($Bq.m^{-2}.hr^{-1}$)

= J (as calculated previously (pg C-30))*3600 s/hr

A = total below grade area of structure in contact with tailings (m^2)

= (10*6) + 1.5*(10+10+6+6) = 108 m^2

B = flux reduction factor

= 0.3

V = volume of structure

$= 10*6*5.5 = 330m^3$

λ = effective removal rate of Rn-222 from structure (i.e. ventilation rate) (hr^{-1})

= triangular distribution (0.3,0.5,1.0)

Thus:

$$C = \frac{J*3600*108*0.3}{330*\lambda} = 3.53E2 *J/\lambda \quad (Bq.m^{-3})$$

The dose conversion factor (DCFIRN) is given by:

$$DCFIRN = 1.44E-4*F \qquad (Sv.a^{-1} \text{ per } Bq.m^{-3})$$

The factor F is calculated as a function of the ventilation rate (λ); or, more specifically, of the mean radon residence time (T_c):

$$T_c = \frac{1}{\lambda} \text{ (hr.)}$$

$$= \frac{60}{\lambda} \text{ min.}$$

for $Tc \leq 120$ min. (and following Lowe et. al. (1984))

$F = 23.15E-6\ T_c^{1/2}*3700$

$= 8.6E-2\ T_c^{1/2}$

for $Tc > 120$ min.

$F = 0.95$

The radon dose is only accumulated for the fraction of time spent indoors. Time indoors is calculated as:

$$\mathrm{OCCFAC} * 14/24 = 0.5833 * \mathrm{OCCFAC}$$

The radon inhalation dose (RID) is then calculated as:

$$\begin{aligned} \mathrm{RID} &= \mathrm{C} * \mathrm{DCFIRN} * (.5833*\mathrm{OCCFAC}) \\ &= (3.53\mathrm{E}2*\mathrm{J}/\quad) * (1.44\mathrm{E}{-4}*\mathrm{F}) * (.5833*\mathrm{OCCFAC}) \\ &= 2.96\mathrm{E}{-2} * \mathrm{OCCFAC} * \mathrm{F} * \mathrm{J} \qquad (\mathrm{Sv.a}^{-1}) \end{aligned}$$

6.0 PARAMETER DESCRIPTIONS AND DISTRIBUTIONS

All parameters specified in the component models described earlier were designated either as constant or variable quantities. Parameters assigned variable quantities were described by one of six different parametric distributions depending on which distribution was considered to best describe the data. Some of the input parameters and, of course, the output results, were calculated as functions of the input quantities.

Where appropriate data were available, they were used to estimate an appropriate parametric distribution. A number of input distributions, such as mean wind speed (WIND), fraction of time wind blows to the receptor (FRACT) and net precipitation (NPRCP) were based on extensive empirical data. In the absence of easily obtainable or appropriate data, the distributions were estimated based on underlying physical principles, trends in similar parameters, and/or professional judgement. Six parametric distributions were available; namely: normal, lognormal, uniform, log-uniform, triangular and Beta.

The model parameters, their logical variable names, definitions and associated units are specified in table C.2. Those input parameters particularly relevant to modelling specific events are summarized in table C.1.

TABLE C.1

Summary of Input Parameters Which Change with Event Modelled

INPUT PARAMETER*

EVENT	ZETA1	RALOAD	EVENT	KRELAX
NULL	0.0	0.0	0.9	0.0
FIRE	0.0	0.0	0.5	0.379
FLOOD	10.0	1500.0	0.1	0.22
DROUGHT	0.0	0.0	0.1	0.22

*where:

ZETA1 = concentration ratio for a shock loading of radium

RALOAD = concentration of radium in lake resulting from a shock load ($Bq.m^{-3}$)

EVENT = fraction of tailings remaining vegetated immediately following an episodic event.

KRELAX = decay constant; based on time for tailings to return to 90% cover.

KEY TO TABLE C.2

Distribution Type		Distribution Specifications
C	Constant	single numerical value
LN	Log normal	geometric mean geometric standard deviation
N	Normal	arithmetic mean arithmetic standard deviation
T	Triangular	minimum, mode (peak), maximum
U	Uniform	minimum, maximum
LU	Log Uniform	minimum, maximum
B	Beta	minimum, maximum, a, b
calculated		numerical value calculated by model

TABLE C.2

LISTING OF PARAMETERS
WITH THEIR DEFINITIONS, PROBABILITY DISTRIBUTIONS AND UNITS

			Parameter Probability Distributions		
Symbol	Definition	Used In Model	Distribution Type	Distribution Specifications	Units
ARBASN	area of the tailings basin watershed	$P_{0,2}$, $X_{o,water}$	C	15.0E5	m^2
AREA	effective tailings surface area	$X_{0,air}$	Calculated		m^2
AREXTL	exposed tailings surface area	$X_{o,air}$	C	50.0E4	m^2
ARLKBT	area of lake bottom	$P_{0,2}$	C	1.6E6	m^2
ARTLSR	total tailings surface area	$X_{o,air}$	C	5.0E5	m^2
BETA	internal variable in model $P_{3,2}$	$P_{3,2}$	Calculated		
BRRA	water to edible portion of aquatic animal type f transfer coefficient	$P_{2,7}$	LN	15.0E-6;3.44	$Bq.g^{-1}.Bq^{-1}.m^3$
BIOWCL	concentration of aquatic biota in the lake water column	$P_{0,2}$	Calculated		$g.m^{-3}$
COVER	fraction of tailings vegetated	$X_{o,air}$,	Calculated		
DARCY	the Darcy velocity	$P_{3,2}$	Calculated		$m.a^{-1}$
DCFING	dose conversion factor for ingestion	$P_{5,10}$, $P_{6,10}$ $P_{2,10}$, $P_{7,10}$	C	3.2E-7	$Sv.Bq^{-1}$
DCFINH	dose conversion factor for inhalation exposure	$P_{1,10}$	C	2.6E-6	$Sv.Bq^{-1}$
DCFIRN	dose conversion factor for inhalation exposure to radon	$P_{1,10}$	C	7.2E-5	$Sv.a^{-1}.Bq^{-1}.m^3$
DECAY	decay constant for flux from lake bottom	$P_{o,2}$	C	0.035	a^{-1}
DISPER	dispersivity	$P_{3,2}$	N	25;10	m
DISPLT	longitudinal dispersion	$P_{3,2}$	Calculated		$m^2.a^{-1}$
DIST	downwind distance (receptor)	$P_{0,1}$	C	3600	m
DISTG	distance along the groundwater flow path from tailings area	$P_{0,3}$, $P_{3,2}$	C	200	m
EBKDFC	effective bulk diffusion coefficient for radon	$X_{o,air}$	Calculated		$m^2.s^{-1}$

Symbol	Definition	Used In Model	Parameter Probability Distributions Distribution Type	Distribution Specifications	Units
EMANAT	emanation coefficient	$X_{o,air}$	T	0.02;0.2;0.9	-
EMIT	source term for air	$X_{o,air}$	Calculated		$Bq.s^{-1}$
ESUBV	the fraction of the foliar deposition retained on the edible portions of the plant (0 to 1):				
	a) lichen, summer forage and above ground vegetation	$P_{1,5}$	C	1.0	-
	b) below ground vegetation	$P_{1,5}$	C	0.1	
EVENT	fraction of tailings remaining vegetated immediately following an episodic event	$X_{o,air}$	C	depends on event (see table C.1)	-
FACTCO	activity coefficient	$X_{o,water}$	Calculated		-
FDEPVE	the fraction of the total deposition retained on the plant surface (0 to 1):				
	a) lichen	$P_{1,5}$	C	0.95	-
	b) summer forage, above and below ground vegetation	$P_{1,5}$	C	0.20	-
FETOPR	feed-to-product p transfer coefficient for animal type a	$P_{2,6}$,$P_{5,6}$	C	1.4E-9	$Bq.g^{-1}.Bq^{-1}.a$
FNPRCP	fraction of precipitation on the tailings drainage basin that infiltrates and enters the deep groundwater flow below the tailings	$P_{0,2}$,$P_{3,2}$ $X_{o,water}$	C	0.15	-
FRACT	fraction of time the wind blows from source to receptor	$P_{0,1}$	N	0.1;0.02	-
FSUBA	fraction of aquatic animal type f that is contaminated (0 to 1):	$P_{7,10}$	C	1.0	-
FSUBP	fraction of animal produce that is contaminated (0 to 1)	$P_{6,10}$	C	0.5	-

Symbol	Definition	Used In Model	Parameter Probability Distributions Distribution Type	 Distribution Specifications	Units
FVEGCN	fraction of vegetation type v consumed by animal type a that is local (0 to 1)	$P_{5,6}$	C	0.5	-
FVEGGR	fraction of vegetation type v grown at the contaminated source (0 to 1)	$P_{5,10}$	C	0.5	-
FWATHM	fraction of water consumed by a human that is contaminated	$P_{2,10}$	C	1.0	-
GWCONC	concentration of radium in groundwater at discharge to the river	$P_{3,2}$	Calculated		$Bq.m^{-3}$
HSUBD	initial mixing depth	$X_{o,air}, P_{0,1}$	U	1.0;3.0	m
HYDCON	hydraulic conductivity	$P_{3,2}$	N	315;300	$m.a^{-1}$
HYDGRD	hydraulic gradient	$P_{3,2}$	N	0.05;0.01	$m.m^{-1}$
INHALE	annual inhalation rate	$P_{1,10}$	C	8400	$m^3.a^{-1}$
JFLUX	contaminant (radium) flux via the groundwater route to the river	$P_{0,2}, P_{3,2}$	Calculated		$Bq.a^{-1}$
JRAWCO	flux of radium from sediments into the water column	$P_{0,2}$	Calculated		$Bq.m^{-2}.a^{-1}$
KPRIME	ratio of the half saturation constant for oxygen to the oxygen concentration at the tailings surface	$X_{o,water}, X_{o,air}$	LN	0.05;2.0	-
KRELAX	constant based on time for tailings to return to 90% cover	$X_{o,air}$	C	depends on event (see table C.1)	a^{-1}
KSUBBI	transfer coefficient for radium from water to aquatic biota	$P_{0,2}$	LN	500E-6;3.2	$m^3.g^{-1}$
KSUBD	sorption or distribution coefficient for radium on suspended solids	$P_{0,2}$	LN	80E-6;3.5	$m^3.g^{-1}$
KSUBDG	distribution coefficient for radium on geologic material along groundwater path	$P_{3,2}$	N	25E-6;10E-6	$m^3.g^{-1}$

Symbol	Definition	Used In Model	Parameter Probability Distributions		Units
			Distribution Type	Distribution Specifications	
KSUBL	mass transfer coefficient of radium into the lake water column from sediments	$P_{0,2}$	LN	0.5;2.24	$m.a^{-1}$
KSUBSO	solubility equilibrium constant for gypsum	$X_{o,water}$, $P_{0,2}$	C	25.0	$moles^2.m^{-6}$
LAMRA	radioactive decay constant for radium	$P_{3,2}$	C	430E-6	a^{-1}
LAMRN	radioactive decay constant for radon	$X_{o,air}$	C	2.1E-6	s^{-1}
LAMWTH	a decay constant accounting for weathering losses	$P_{1,5}$	C	5.73E-7	s^{-1}
LSUBC	radon diffusion length in the cover	$X_{o,air}$	U	0.5;1.5	m
LSUBT	radon diffusion length in tailings	$X_{o,air}$	Calculated		m
MPCH2O	percent water (by weight) in tailings	$X_{o,air}$	T	5.0;15.0;25.0	-
NPRCP	net precipitation (i.e. after evapotranspiration losses)	$X_{o,water}$, $P_{0,2}$ $P_{3,2}$	N	0.4;0.1	$m.a^{-1}$
NSUBW	number of winter months per year	$X_{o,air}$	C	5.0	-
OCCFAC	occupancy factor, or fraction of year spent at the location (0 to 1)	$P_{1,10}$	T	0.3;0.6;0.9	-
O2CONC	oxygen concentration at the the tailings surface	$X_{o,water}$	C	9.04	$moles.m^{-3}$
O2DIFF	oxygen diffusivity through the tailings	$X_{o,water}$	LN	70.0;1.35	$m^2.a^{-1}$
PHI	concentration of sulphate in porewater	$X_{o,water}$	Calculated		$moles.m^{-3}$
POROSG	porosity of the geologic material	$P_{3,2}$	N	0.3;0.025	$m^3.m^{-3}$
PROBIO	net biomass productivity	$P_{0,2}$	LN	30.0;1.15	$g.m^{-2}.a^{-1}$
QSUBI	flowrate of the freshwater in the river at the point of discharge to the lake excluding the tailings sub-basin discharge	$P_{0,2}$	Calculated		$m^3.a^{-1}$
QSUBO	total water outflow from the lake	$P_{0,2}$	Calculated		$m^3.a^{-1}$

Symbol	Definition	Used In Model	Parameter Probability Distributions Distribution Type	 Distribution Specifications	Units
QSUBR	total flow in river system at end of reach with discharge to the lake including the tailings sub-basin discharge	$P_{0,2}$	Calculated		$m^3.a^{-1}$
QVEG	annual intake of vegetation type v (dry wt. basis) by animal type a:	$P_{5,6}$			$g.a^{-1}$
	a) lichen by caribou		C	1490E3	$g.a^{-1}$
	b) summer forage by caribou		C	1065E3	$g.a^{-1}$
	c) above and below ground vegetation		-	0.0	-
QVOLSR	volumetric rate of groundwater flow from the tailings area	$P_{3,2}$	Calculated		$m^3.a^{-1}$
RAAIR	airborne concentration of radium	$P_{0,1}$	Calculated		$Bq.m^{-3}$
RACNTA	radium concentration in the tailings	$X_{o,air}$	U	5.0;15.0	$Bq.g^{-1}$
RAGPTA	radium content of gypsum in tailings	$X_{o,water}$	B	2500;10,000;a=1.5;b=.5	$Bq.mole^{-1}$
RALOAD	concentration of Radium resulting from a shock load	$P_{o,2}$	C	depends on event (see table C.1)	$Bq.m^{-3}$
RALTOT	concentration of total radium in the lake water column	$P_{0,2}$	Calculated		$Bq.m^{-3}$
RAPOWA	radium concentration in the tailings porewater	$X_{o,water}, P_{0,2}, P_{3,2}$	Calculated		$Bq.m^{-3}$
RARTOT	concentration of total radium in the river at its point of discharge into the lake	$P_{0,2}$	Calculated		$Bq.m^{-3}$
RATI	concentration of radium in the river system upstream of the tailings discharge	$P_{0,2}$	C	37.0	$Bq.m^{-3}$
RESDEP	effective resuspension depth	$X_{o,air}$	U	1.0E-3;1.0E-2	m
RESFAC	resuspension factor for dust from tailings	$X_{o,air}$	LU	1.0E-9;1.0E-5	m^{-1}
RESTIM	decay constant based on lake residence time	$P_{o,2}$	C	0.25	a^{-1}
RETFAC	retardation factor	$P_{3,2}$	Calculated		-
RHOBAS	bulk density of the geologic material	$P_{3,2}$	N	1.92E6;0.15E6	$g.m^{-3}$
RHOTAL	tailings density	$X_{o,air}, X_{o,water}$	N	1.4E6;0.1E6	$g.m^{-3}$

			Parameter Probability Distributions		
Symbol	Definition	Used In Model	Distribution Type	Distribution Specifications	Units
RLOAD	radium loading due to soil erosion	$X_{o,water}$	Calculated		$Bq.a^{-1}$
RNSOUR	source emission rate for radon	$X_{o,air}$	Calculated		$Bq.s^{-1}$
SIGBIO	sedimentation velocity of biomass	$P_{0,2}$	LN	12.0;1.15	$m.a^{-1}$
SIGSS	sedimentation velocity of suspended solids	$P_{0,2}$	LN	24.5;1.1	$m.a^{-1}$
SIGZED	vertical dispersion coefficient	$P_{0,1}$	LN	60.0;1.73	m
SSL	concentration of suspended solids in the water column	$P_{0,2}$	Calculated		$g.m^{-3}$
SSR	suspended soils concentration in the river at its point of discharge to the lake	$P_{0,2}$	LN	4.0;2.0	$g.m^{-3}$
SULPRD	average yearly sulphate production rate	$X_{o,water}$	LN	1.4E-6;1.73	$moles.(g.a)^{-1}$
TEXPDP	duration of plant exposure for vegetation type v to atmospheric deposition:				
	a) lichens	$P_{1,5}$	C	100.0E6	s
	b) summer forage	$P_{1,5}$	C	2.592E6	s
	c) above and below ground vegetation	$P_{1,5}$	C	5.184E6	s
TIME	time from placement of tailings	$P_{3,2}$	U	50;2500	a
THICK	clean cover thickness : Option #1	$X_{o,air}$	C	0.0	m
	Option #2	$X_{o,air}$	T	0.5;1.0;2.0	m
			T	0.5;1.0;2.0	
USUBA	annual human ingestion rate of aquatic animal type f	$P_{7,10}$	C	8000	$g.a^{-1}$
USUBP	the annual human ingestion rate of animal produce type p	$P_{6,10}$	C	79.0E3	$g.a^{-1}$
USUBV	the annual human ingestion rate of vegetation type v:				
	a) lichen and summer forage	$P_{5,10}$	C	0.0	$g.a^{-1}$
	b) above ground vegetation	$P_{5,10}$	C	157.0E3	$g.a^{-1}$
	c) below ground vegetation	$P_{5,10}$	C	70.0E3	$g.a^{-1}$

			Parameter Probability Distributions		
Symbol	Definition	Used In Model	Distribution Type	Distribution Specifications	Units
USUBW	annual human intake of water	$P_{2,10}$	C	0.6	$m^3.a^{-1}$
VELDEP	deposition velocity	$P_{1,5}$	C	0.02	$m.s^{-1}$
WIND	wind speed	$X_{o,air}, P_{0,1}$	N	5.3;0.5	$m.s^{-1}$
WTSFLX	winter to summer radon flux ratio	$X_{o,air}$	LN	0.02;2.15	-
XOGWRA	source term release of radium to the groundwater flow component	$X_{o,water}$	Calculated		$Bq.s^{-1}$
XOSWRA	source term release of radium to the surface water flow component	$X_{o,water}$	Calculated		$Bq.s^{-1}$
YDENST	the yield density of vegetation type v:				
	a) lichen	$P_{1,5}$	C	500.0	$g.m^{-2}$
	b) summer forage	$P_{1,5}$	C	750.0	$g.m^{-2}$
	c) above and below ground vegetation	$P_{1,5}$	C	2000.0	$g.m^{-2}$
ZETA	concentration ratio for dissolved radium between interstitial (sediment) water and the lake water.	$P_{0,2}$	U	0.5;1.5	-
ZETA1	concentration ratio for a shock loading of radium in lake.	$P_{0,2}$		depends on event (see table C.1)	-

7.0 CALCULATION METHODOLOGY

All consequences, for all events and receptors, were calculated by evaluating the appropriate models for 200 simple random trials using a probabilistic analysis computer program (RANSIM), developed by SENES Consultants Limited (SENES 1985). Consequences (or effects) of each event were determined in a variety of ways. The results are presented in tables C-3 to C-6. For each entry in the tables (i.e. each event - consequence calculation), the mean and standard deviation (in brackets) of the 200 calculated values are indicated.

The maximum annual dose and the 50 year average annual dose to both the reference receptor and the tailings intruder were calculated. As expected, the maximum annual dose and the 50 year average annual dose to the intruder were found to be equal (within the error expected from such random trials). This was also true of the reference receptor for the null event.

As mentioned earlier the downstream receptor was considered more representative of the surrounding population. Hence, cumulative effects, over appropriate time periods, were calculated for this receptor. Such results are sufficient to allow calculation of a "population dose".

8.0 RESULTS

8.1 Maximum Annual Dose

The maximum annual dose to the receptor was assumed to occur in the first year following any episodic event. Since the models as formulated were designed to calculate an annual dose, no time dependency was required for these calculations. The "maximum annual dose" for both the null event (reference receptor) and the

Table C.3

Maximum Annual Dose (Sv/a)

	Radon	Air Pathways				Water Pathways				Total
EVENT	Inhalation	Inhalation	Vegetables	Meat	Total	Ingestion	Fish	Total	External	Dose
Null	8.44E-6 *	5.31E-7	3.47E-6	3.76E-8	4.04E-6	6.30E-5	2.34E-5	8.64E-5	--	9.89E-5
	(8.36E-6)**	(13.7E-7)	(8.88E-6)	(9.62E-8)	(10.3E-6)	(2.17E-5)	(4.48E-5)	(5.50E-5)	--	(5.69E-5)
Fire	8.44E-6	1.19E-6	7.76E-6	8.41E-8	9.03E-6	9.87E-5	3.55E-5	1.34E-4	--	1.52E-4
	(8.36E-6)	(3.07E-6)	(19.8E-6)	(21.5E-8)	(23.1E-6)	(2.45E-5)	(5.94E-5)	(.686E-4)	--	(.740E-4)
Flood	8.44E-6	1.59E-6	1.04E-5	1.13E-7	1.21E-5	6.16E-4	2.17E-4	8.34E-4	--	8.54E-4
	(8.36E-6)	(4.12E-6)	(2.66E-5)	(2.89E-7)	(3.10E-5)	(2.34E-4)	(3.44E-4)	(4.68E-4)	--	(4.71E-4)
Drought	1.14E-5	1.59E-6	1.04E-5	1.13E-7	1.21E-5	1.14E-4	4.02E-5	1.54E-4	--	1.78E-4
	(1.07E-5)	(4.12E-6)	(2.66E-5)	(2.89E-7)	(3.10E-5)	(.327E-4)	(6.16E-5)	(.761E-4)	--	(.861E-4)
Intrusion	8.68E-2							2.37E-1		3.24E-1
	(8.38E-2)							(.869E-1)		(1.39E-1)

* mean value of 200 random trials

** standard deviation of 200 random trials

Table C.4

Average Annual Dose (Sv/a)

	Radon		Air Pathways			Water Pathways				Total
EVENT	Inhalation	Inhalation	Vegetables	Meat	Total	Ingestion	Fish	Total	External	Dose
Null	7.91E-6*	5.84E-7	3.82E-6	4.14E-8	4.45E-6	6.56E-5	1.84E-5	8.40E-5	--	9.64E-5
	(10.3E-6)**	(13.3E-7)	(9.40E-6)	(10.2E-8)	(10.8E-6)	(2.09E-5)	(2.79E-5)	(3.77E-5)	--	(3.99E-5)
Fire	7.91E-6	6.34E-7	4.15E-6	4.50E-8	4.83E-6	6.78E-5	1.91E-5	8.68E-5	--	9.96E-5
	(10.3E-6)	(14.4E-7)	(10.2E-6)	(11.1E-8)	(11.7E-6)	(2.11E-5)	(2.91E-5)	(3.88E-5)	--	(4.12E-5)
Flood	7.91E-6	7.24E-7	4.74E-6	5.14E-8	5.52E-6	1.45E-4	4.31E-5	1.88E-4	--	2.02E-4
	(10.3E-6)	(16.5E-7)	(11.7E-6)	(12.7E-8)	(13.4E-6)	(.576E-4)	(7.59E-5)	(1.07E-4)	--	(1.08E-4)
Drought	8.03E-6	7.24E-7	4.74E-6	5.14E-8	5.52E-6	6.95E-5	1.97E-5	8.92E-5	--	1.03E-4
	(10.4E-6)	(16.5E-7)	(11.7E-6)	(12.7E-8)	(13.4E-6)	(2.09E-5)	(3.05E-5)	(3.98E-5)	--	(.428E-4)
Intrusion	7.88E-2							2.47E-1		3.26E-1
	(7.27E-2)							(.893E-1)		(1.33E-1)

* mean value of 200 random trials

** standard deviation of 200 random trials

TABLE C-5

Cumulative Dose to Downstream Receptor (Sv)

	Radon		Air Pathways			Water Pathways			Total	
EVENT	Inhalation	Inhalation	Vegetables	Meat	Total	Ingestion	Fish	Total	Dose	Time(YR)
Null	1.25E-6*	5.61E-8	3.82E-7	4.14E-9	4.42E-7	6.56E-6	1.44E-6	8.00E-6	9.70E-6	1
	(1.57E-6)**	(13.8E-8)	(8.47E-7)	(9.18E-9)	(9.89E-7)	(2.21E-6)	(3.62E-6)	(4.56E-6)	(4.89E-6)	
Fire	2.51E-5	1.35E-6	9.17E-6	(9.94E-8)	1.06E-5	1.40E-4	3.08E-5	1.71E-4	2.06E-4	20
	(3.14E-5)	(3.33E-6)	(20.3E-6)	(22.0E-8)	(2.34E-5)	(.448E-4)	(7.67E-5)	(.953E-4)	(1.03E-4)	
Drought	5.09E-5	2.92E-6	1.98E-5	2.15E-7	2.30E-5	2.82E-4	6.21E-5	3.44E-4	4.18E-4	40
	(6.35E-5)	(7.22E-6)	(4.40E-5)	(4.77E-7)	(5.14E-5)	(.885E-4)	(15.4E-5)	(1.91E-4)	(2.07E-4)	
Flood	1.25E-4	6.29E-6	4.28E-5	4.64E-7	4.95E-5	1.04E-3	2.36E-4	1.28E-3	1.46E-3	100
	(1.57E-4)	(15.6E-6)	(9.49E-5)	(10.3E-7)	(11.1E-5)	(.342E-3)	(5.85E-4)	(.738E-3)	(.752E-3)	

* mean value of 200 random trials

** standard deviation of 200 random trials

TABLE C-6

Cumulative Flux to Environment (GBq)

EVENT	Ra Flux to Water	Ra Flux to Air	Rn Flux to Air	Time (YR)
NULL	2.40*	5.80	2.90E4	1
	(.846)**	(12.5)	(2.52E4)	
FIRE	5.17E1	1.39E2	5.80E5	20
	(1.70E1)	(3.01E2)	(5.05E5)	
DROUGHT	1.01E2	3.01E2	1.18E6	40
	(.328E2)	(6.51E2)	(1.02E6)	
FLOOD	2.70E2	6.50E2	2.90E6	100
	(.864E2)	(14.0E2)	(2.52E6)	

* mean value of 200 random trials

** standard deviation of 200 random trials

intruder receptor is assumed to represent such consequences at any time.

Results of this analysis are summarized in table C-3. The doses to the reference receptor via six distinct mechanisms (as well as total dose, and sub-totals due to air and water pathways) are presented in the table. As described previously, and indicated in the table, the dose to the intruder arises only from radon inhalation and external exposure.

The results show some expected trends. Since the radon pathway is not affected by the fire or flood events, the radon inhalation doses for these events are equal to that for the null event. Furthermore, neither the fire nor drought events produce large increases in the maximum annual dose. Conversely, the flood event dramatically increases dose via the water pathways and hence total dose. The tailings intruder is exposed to an annual dose approximately three orders of magnitude greater than the maximum annual dose to the reference receptor for any episodic event.

8.2 50 Year Average Annual Dose

The calculation of an average annual consequence involved simulation of the time dependent behavior of the system following each episodic event. The calculations were consequently somewhat more involved. The procedure used is summarized below:

- For Each Trial:

i) - time invariant input parameters were selected

ii) - for time = 0,5,10...45,50 years
- time variant input parameters; net annual precipitation

(NPRCP) and mean annual wind speed (WIND), were sampled from appropriate distributions (i.e. with variance reduced by $1/\sqrt{5}$).

- the models were evaluated. i.e. several annual consequences (eg. dose via air, water etc.) were calculated.
- a running total of the sum of these annual consequences was maintained.

iii) - after the time = 50 year calculation was performed, the cumulative total of the annual consequences was divided by the number of such consequences calculated; (in this case 11). The result was an average annual value for the 50 year period considered.

- Steps (i), (ii) and (iii) were repeated for each of 200 trials.

Mean value and standard deviations calculated from the 200 trials for each consequence (dose) are presented in table C-4. The dose mechanisms (i.e. pathways and receptors) considered are the same as in table C-3.

The 50 year average annual doses to the tailings intruder and to the reference receptor for the null event should equal the respective maximum annual doses (as presented in table C-3). The differences noted between the results are due to the random nature of the simulation and are completely expected.

A comparison of tables C-3 and C-4, gives the impression that the episodic events (especially fire and drought) produce only a marginal increase in dose to the reference receptor. This is since these events only affect the system for 10 to 20 years, with the majority of the effects concentrated in the first 5 years following the event.

8.3 Cumulative Consequences

Cumulative doses to the downstream receptor were calculated for the duration of the various episodic events. Cumulative fluxes of radium to air and water and radon to air were also calculated using the same methodology. Duration of events (i.e. the time required to return (at least nearly) to pre-event (null conditions) were modelled as:

NULL	1 year	
FIRE	20 years	($\Delta t=2$ years)
DROUGHT	40 years	($\Delta t=4$ years)
FLOOD	100 years	($\Delta t=5$ years)

The calculation methodology employed is outlined below:

- For each trial

i) a vector of input parameters was selected (Note: time variant input parameters NPRCP and WIND were held constant at their long-term mean values).

ii) for time = 0, Δt, $2\Delta t$...n years.
   - the models were evaluated (i.e. several annual consequences were calculated).
   - for all consequences, at all times except t = 0, a geometric mean for the previous time step was calculated:

$$X_t = (X_t{*}X_{t-\Delta t})^{1/2}$$

where:

$\overline{X}_t$ = geometric mean value of consequence in interval $(t-\Delta t, t)$

X_t = consequence at time t

$X_t - \Delta t$ = consequence at time $t-\Delta t$

The total magnitude of each consequence (C_t) over the same time interval was calculated as:

$$C_t = X_t * \Delta t$$

A cumulative total for each consequence was maintained.

iii) - after the final time step, the cumulative consequences (C_t) represent the total cumulative consequences for the event modelled. These values were saved.

- Steps (i), (ii) and (iii) were repeated for each of 200 trials.

The cumulative consequences to the downstream receptor are summarized in table C-5. Cumulative fluxes of radium and radon for the time periods indicated are presented in table C-6. Again, a number of expected trends are apparent. For instance, the radon pathway is unaffected by a forest fire event. Thus, the dose via the radon pathway for the 20 year period modelled for forest fire (2.51E-5 Sv/a) should be equal to twenty times the radon dose for the null event (1.25E-6). This is found to be true.

REFERENCES (Appendix C)

Anspaugh, L.R., Shinn, J.J., Phelps, P.L., and Kennedy, N.C., 1975. "Resuspension and Redistribution of Plutonium in Soils." Health Physics 29, pp. 571-582.

Blair, R.D., Cherry, J.A., Lim, T.P. and Vivyurka, A.J., 1980. "Groundwater Monitoring and Contaminant Occurrence at an Abandoned Tailings Area, Elliot Lake Ontario". Proceedings of the First International Conference on Uranium Mine Waste Disposal, Vancouver, May 19-21.

Chambers, D.B., Lowe, L.M., Cassaday, V.J., Nantel, J.H. and Archibald, J.F., 1980. "Development and Use of Radon Source Terms in Environmental Impact Assessments". Presented at the 25th Annual Meeting of the Health Physics Society, Seattle, Washington.

Chambers, D.B., Mernagh, J.R., Torrie, R.T., 1981 "Design for Radiation Protection in the Mining of High Grade Uranium Ore." Proceedings of : International Conference on Radiation Hazards in Mining: Control, Measurement, and Medical Aspects, October 4-9, 1981 (M. Gomez, ed.)

Cherry, J.A., Blackport, R.J., Dubrovsky, N., Gillham, R.W., Lim, T.P., Murray, D., Reardon, E.J. and Smith, D.J.A., 1980. "Subsurface Hydrology and Geochemical Evolution of Inactive Pyritic Tailings in the Elliot Lake Uranium District, Canada." Proceedings of the Third Symposium on Uranium Tailings Management, Colorado State University, Fort Collins, Colorado, Nov. 24-25.

References-Appendix C (continued)

Gilbert, T.L., Chee, P.C., Knight, M.J., Peterson, J.M., Roberts, C.J., Robinson, J.E., Tsai, S.Y.H., Yuan, Y.C., 1983. "Pathways Analysis and Radiation Dose Estimates for Radioactive Residues at Formerly Utilized MED/AEC Sites". U.S. Department of Energy.

Golder Associates, 1981a. "Hydrogeological Investigation, Williams Lake Management Area." Report to Denison Mines Limited.

Golder Associates, 1981b. "Additional Hydrogeochemical Monitoring, 1981, Williams Lake Management Area." Report to Denison Mines Limited.

Halbert, B.E., Scharer, J.M., Knapp, R.A., and Gorber, D.M., 1983. "Determination of Acid Generation Rates in Pyritic Mine Tailings". Presented at the 56th Annual Conference of the Water Pollution Control Federation, Atlanta, Georgia, October 2-7.

Hanna, S.R., 1982. "Review of Atmospheric Diffusion Models for Regulatory Applications." World Meteorological Organization Technical Note No. 177, Geneva.

Johnson, J.R. and Dunford, D.W., 1983. "Dose Conversion Factors for Intakes of Selected Radionuclides by Infants and Adults." AECL-7919. Atomic Energy of Canada Limited, Chalk River.

References-Appendix C (continued)

Linsley, G.S., 1978. "Resuspension of the Transuranium Elements - A Review of Existing Data". National Radiological Protection Board, NRPB-R75.

Nordstrom, D.K., 1982. "Aqueous Pyrite Oxidation and the Consequent Formation of Secondary Iron Minerals". In Acid Sulphate Weathering, Soil Science Society of America, 37-55.

Rogers, V.C., Overmeyer, R.F., Putzig, K.M., Jensen, C.M., Nielson, K.K., and Sermon, B.W., 1980. "Characterization of Uranium Tailings Cover Materials for Radon Flux Reduction." Prepared by Ford, Bacon and Davis Utah, Inc., for U.S. Nuclear Regulatory Commission, Report NUREG/CR-1081, FBDU-218-2.

Sehmel, G.A., 1980. "Particle Resuspension: A Review." Environment International, Vol. 4, pp. 107-129.

SENES Consultants Ltd., 1984 (for the Atomic Energy Control Board). "Documentation of Predictive Computer Models For an Underground Mine Ventilation System."

SENES Consultants Limited, 1984. "A Study to Develop and Demonstrate Techniques for the Probabilistic Assessment of the Long-Term Effects of Uranium Mill Tailings in Canada - Phase I." Research Report Prepared for the National Uranium Tailings Program, CANMET, EMR, under Supply and Services Canada Contract No. OSQ83-00236.

References-Appendix C (continued)

SENES Consultants Limited, 1985. "A Study to Develop and Demonstrate Techniques for the Probabilistic Assessment of the Long-Term Effects of Uranium Mill Tailings in Canada - Phase I." Research Report Prepared for the National Uranium Tailings Program, CANMET, EMR, under Supply and Services Canada Contract No. 0SQ84-00207.

Silver, M., and Ritcey, G.M., 1982. "A Simulation of the Effects of Bacteria, Organics and Salt Solutions on Uranium Mine/Mill Tailings from Elliot Lake, Ontario". In Waste Treatment and Utilization, Theory and Practice of Waste Management, Vol. 2, M. Moo-Young (Ed.), Pergamon Press, 489-501.

Shumate, K.S., Smith, E.E., Dugan, P.R., Brant, R.A. and Randles, C.E., 1971. "Acid Mine Drainage, Formation and Abatement". E.P.A. Rept. 14010 FPR 04/71.

Stumm, W., and Morgan A.T., 1981. "Aquatic Chemistry". 2nd Ed., John Wiley pub., New York.

Turner, D.B., 1969. "Workbook of Atmospheric Dispersion Estimates." U.S. Dept. of Health, Education and Welfare, Cincinnati, Ohio.

United States Nuclear Regulatory Commission (NRC), 1982. "Calculational Models for Estimating Radiation Doses to Man from Airborne Radioactive Material Resulting from Uranium Milling Operations." Regulatory Guide 3.51.

References-Appendix C (continued)

United States Nuclear Regulatory Commission (NRC), 1980. "Final Generic Environmental Impact Statement on Uranium Milling". NUREG-0706.

United States Nuclear Regulatory Commission (NRC), 1983 "Trench Design and Construction Techniques for Low-Level Radioactive Waste Disposal". NUREG/CR-3144

Zettwoog, P., Fourcade, N., Campbell, F., and Caplan, H.S., 1981. "The Effect of Freezing on the Emanation of Radon from Uranium Ore and Tailings Samples". Health Physics, Vol. 41, pp. 410-411.

APPENDIX D

SOME FUNDAMENTAL ISSUES IN THE DEVELOPMENT OF A COHERENT RISK MANAGEMENT STRATEGY FOR URANIUM MILL TAILINGS

Prepared by
Prof. M. Granger Morgan
Dept. of Engineering and Public Policy
Carnegie-Mellon University

for SENES Consultants Limited

1.0 INTRODUCTION

In undertaking risk analysis and management on a problem such as uranium mill tailings (UMT), there are three interrelated factors which can profoundly influence the conclusions that one reaches. These are:

- How one frames and places boundaries on the problem,
- What objective function one adopts in performing the analysis, and
- What general risk management strategy one adopts.

In practice people often fail to think carefully about these issues. Instead they adopt specific approaches without realizing they have made any choices. Those choices may have greater impact on the conclusions that are reached than any of the details of the subsequent analysis, including the characterization and propagation of scientific uncertainties.

The conventional paradigm of policy analysis calls for choices about these factors to be made first and then for analysis to follow to aid in selecting one of a variety of possible alternative actions. However, until they have had a chance to examine some alternatives people often do not know what they want. Thus, some workers (1,2) have argued that before objective functions and general strategies are chosen, they too should be analyzed and alternatives considered.

2.0 HOW SHOULD WE THINK ABOUT UMT RISKS

There are a number of rather different ways in which one might think about or "frame" the problem of UMT risks. For simplicity in what follows I will discuss only radon, but similar arguments could be constructed for other UMT hazards such as ground and surface water contamination.

First, one might adopt what I will call a "no significant impacts with no tradeoffs" approach. Under this view all human activities such as mining must be managed so as to impose no significant changes or loadings on the environment. Under this approach radon emissions, from human activities such as uranium mining, would be viewed as "wrong" and would not be allowed. Issues of net cost and tradeoffs would be viewed as irrelevant, just as they as when someone violates one of my basic rights under common law.

Second, one might adopt an approach that attempts to obtain "maximum net benefit through tradeoffs" on the scale of the single technology. Under such a strategy one would accept some externally determined value of the appropriate marginal rate of social investment to prevent mortality (such as $3,000/person-sievert) and then undertake as much reduction of radon exposure from the specific technology as one can technically achieve given the selected investment rate.

The externally specified investment rate could be chosen in a variety of ways. Empirical studies by Graham and Vaupel (3) and by Schwing (4) indicate that these rates vary by several orders of magnitude across U.S. society. The situation in Canada is almost certainly similar.

If one ignores the behavioral studies of Slovic et al. (5) and adopts Sidall's view that society should use essentially the same rate of investment per death averted in all activities, then one might argue that it is inappropriate to spend significantly more per person-sievert on reducing radon exposure from UMT piles than society spends on reducing radon exposure from cellar floors and walls and from building materials in homes. Such a view can also be described as a strategy of "maximum net benefit through tradeoff", but now the scale has been broadened from the single technology to encompass the entire society.

While one could construct a number of other approaches, for simplicity, let me consider just two others, which I will call the "no significant change in nation-wide background" strategy and the "no significant change in regional background" strategy. Natural background levels of radon are significant, and show considerable spatial and temporal variation. Many different human activities influence these levels. Plowing of fields increases radon release to the atmosphere. Flooding of reservoirs and paving of highways reduces radon emission levels. One could adopt the position that total radon releases from all human activities must be managed so as to yield no significant departure from a statistically described background level on either a national or on a regional basis. Choosing this level and its associated statistics would involve a number of data problems and value judgements, but they are probably no more difficult than the judgements required by any of the other approaches outlined above.

Process-Based Approaches

All of the approaches that I have described focus on selecting an objective and then implementing it. Political scientists would point out that frequently society does not solve its problems in this way. Instead it adopts "process-based" approaches. Under a process-based approach, the choice of what will be done is left to the operation of some political process. For example a referendum might be held, or alternatively, interest groups may lobby an appointed decision maker who makes trade-offs among these interests. Arguments about objectives of the sort I have advanced in the preceding section may be used as vehicles of political persuasion in such an approach, but their role is typically secondary.

In a purely political world in which there are no hard constraints and eveything is freely exchangeable such an approach may be a feasible way to solve specific societal problems. However, for problems like risk management of UMT, which involve physical laws and constraints which will not respond to political considerations, my personal view is that adopting a process-based approach is a poor way to proceed because it holds a substantial likelihood of producing decisions which are not consistent with physical reality, not efficient, and not consistent in terms of the actual level of risk management adopted for similar risks across the society. While these arguments are persuasive to me, I must note that at least some political scientists would probably argue that they simply reflect the naive disciplinary prejudices of a physical scientist.

While I do not consider a process-based approach to be appropriate as the primary strategy for solving specific societal risk management problems such as the management of known and possible risks from UMT, I do consider a process-based approach to be the appropriate strategy by which society chooses among the various objective-based approaches that might be adopted to solve broad classes of social problems such as risk management.

Choosing How We Will Think About and Approach the Problem

In Section 2 we sketched five possible objective-based approaches that might be taken to the UMT radon risk management problem. With a bit of effort the reader can probably develop several additional possibilities. Before setting out to "solve" the UMT problem I think it is important to identify a number of such alternatives and then develop each one at some length so as to be able to understand its potential strengths and limitations.

Having done this, how should one go about choosing an alternative? It strikes me that several factors should enter the decision:

- the extent to which the approach lends itself to practical implementation (e.g. are the required data available, do uncertainties swamp or mask the choices that must be made, etc.)
- The extent to which the approach yields results which are considered ethically appropriate
- The extent to which the approach is socially and politically feasible.

In making a choice there is of course no reason why one can't pick attractive elements of several alternatives to combine into hybrid strategies. For example, one might adopt the single technology tradeoff strategy to deal with exposure of local residents and the no significant change in background strategy to deal with exposure of more distantly located people.

Before one can properly evaluate these alternatives one must think carefully about the general risk management strategy that will be adopted in applying the alternative. Two choices are particularly important:

- the choice between a "one-time-solution" strategy and an "adaptive-look-ahead" strategy, and
- the choice between a "generic" strategy and a "site specific" strategy.

In approaching problems in environmental risk, many people have a tendency to try to produce "one-time-solutions" that will, once and for all, solve the problem definitively. Sometimes this is possible. Often, because of uncertainty about the future, or the nature of the problem, such a strategy is physically and/or economically infeasible. In such circumstances a solution that does the best for the near future while preserving options for future flexibility as uncertainties are resolved and technology evolves, mades a great deal of sense.

After examining the UMT problem in some considerable detail over the past two years my own conclusion is that, despite political and other pressures to adopt a "one-time-solution-strategy" such an approach is technically infeasible for UMT. There is no way on a time scale of decades or centuries, let along longer time periods, that the integrity and stability of a pile can be absolutely assured unless one occasionally inspects it and takes corrective actions if and when they are required. To adopt a strategy which attempts to deny this reality, and which claims to remove the need for regular inspection, strikes me as a recipe for increasing the likelihood of future difficulties.

A regular program of inspection need not be expensive. Various institutional alternatives, such as sinking funds, can assure the economic viability of such an approach.

Opponents to an "adaptive-look-ahead" strategy for UMT management advance a variety of socially and ethically attractive arguments for adopting a "one-time-solution". I find these arguments appealing. They do not, however, overcome the basic fact that a "one-time-solution" is technically infeasible. To ignore this technical reality for social and political reasons strikes me as setting oneself up for trouble.

The other choice that must be made is between a generic and site-specific approach. Once again I think the technical dimensions of the problem dictate the answer. Much as it would be nice to specify a single "generic" solution for the entire UMT problem, the enormous variability from site to site means that only an approach that allows considerable site-specific flexibility is likely to yield reasonable results.

Having decided that the science of the problem mandates an "adaptive look ahead/site specific" strategy we can return to the question of choosing among alternative approaches in terms of their technical and institutional feasibility, ethical appropriateness and social and political feasibility. Table 1 outlines a few of the issues that should be considered. Since the point of this paper is to initiate discussion, not solve the problem, I will not develop the arguments further or argue for the choice of any one approach over another. Indeed, the discussion of the preceding section suggests that this is not the sort of choice that consultants, technical analysts, or agency staffers should be making. Once the alternatives have been carefully articulated and discussed, it is a choice that should be made by a socially accepted political process in Canada, such as through a decision by the appropriate Federal Ministry.

Table 1

EVALUATION OF THE ALTERNATIVE APPROACHES TO UMT RISK MANAGEMENT INTRODUCED AND DISCUSSED IN SECTION 2 OF THE PAPER

Alternative Approach	Feasibility	Ethical Appropriateness	Social and Politial Feasibility
No significant impacts with no trade-offs	Feasibility depends upon how "significant" is defined. If a very restrictive definition is adopted the approach could required heroic measures and be very expensive	One must resolve the question of why radon from human activity should be treated differently from radon from other sources.	Likely to be attractive among some environmental groups. Likely to be unattractive to industry. High potential costs could lead to political complications
Maximize net benefit through trade-off on the scale of:			
single technology	If approximations are allowed, feasible in the short run with an adaptive-look-ahead strategy. Not a meaningful exercise over a long time horizons	Appropriate to utilitarians. Depending on how investment rate to prevent mortality is selected, may be appropriate in other ethical systms	May not capture everything about the risk which is important to people (see Slovic et al. (5). Explicit identification of investment rate to prevent mortality may be socially contentions.
all of society	Probably not a meaningful exercise even over fairly short time horizons	Appropriate if one is a utilitarian. May not be appropriate in other ethical systems such as libertarian.	
No significant change in background on:			
regional scale	If approximations are allowed, feasible on a regional scale.	One must resolve the question of whether radon from human activity should be treated differently from radon from other sources.	Has advantage that nature rather than man is allowed to set the standard. Thus political "blame" less likely to be attached
national scale	Not likely to be physically meaningful on a national scale.		

Isn't This All Just Academic Nonsense?

The initial reaction of some people who have been engaged in the day-to-day process of UMT regulatory decision making may be that the discussion in this paper is just so much broad philisophical academic nonsense. To these readers I say... be careful. The U.S. has recently gone through the process of developing UMT risk management standards. The results contain serious technical and philosophical internal inconsistencies. This has occurred in large part I think because we charged in and tried to generate solutions without thinking through and developing a philosophically defensible and consistent approach to the problem. I hope Canada can learn from out mistakes.

REFERENCES

1. Henry S. Rowen, 1976. "Policy Analysis as Heuristic Aid: The Design of Means, Ends, and Institutions." in When Values Conflict, L.H. Tribe, C.S. Schelling and J. Voss (eds.), Ballinger.

2. March, James G., 1976. "The Technology of Foolishness." in Ambiguity and Choice in Organizations, J.G. March and J.P. Olsen (eds.) Universitetsforlaget, Oslo.

3. Graham, John D. and Vaupel, James W., 1981. "Value of Life: What Difference Does it Make?" Risk Analysis, 1, pp. 89-95, March.

4. Schwing, Richard C., 1980. "Trade-Offs." in Societal Risk Assessment: How Safe is Safe Enough?" R.C. Schwing and W.A. Albers (eds.) Plenum.

5. Slovic, Paul, Fischhoff, Baruch and Lichtenstein, Sarah, 1980. "Facts and Fears: Understanding Perceived Risk." in Societal Risk Assessment: How Safe is Safe Enough?. R.C. Schwing and W.A. Albers (eds.), Plenum.